Understanding and Benchmarking Suppression Systems for Post-flashover Informal Settlement Fires

by

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Declaration

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Abstract

Currently there are more than one billion people residing in informal settlements worldwide. The increasing number of people residing in informal settlements worldwide is attributed to an overall rise in the world population and an increasing rate of urbanisation. Within the South African context, an alarming increase in the number of informal settlement fires has been documented since the turn of the millennium and it is of serious concern to see how little progress has been made in terms of fire safety within these poverty stricken communities. It is with this backdrop that this work seeks to understand the use of existing active fire suppression systems for post-flashover informal settlement fires, in the hope of improving the knowledge pertaining to these issues and thereby potentially enhancing fire safety within informal settlement communities. The work provides insight and technical guidance for fire brigades, municipalities and organisations working in informal settlements who are seeking to improve fire safety.

In this work a novel testing methodology is developed for benchmarking the suppression performance of various existing fire protection strategies in post-flashover informal settlement fires. A series of nine full-scale experiments are conducted on a single representative steel cladded informal settlement dwelling during which the suppression performance of various fire protection strategies is measured and analysed. The fire protection strategies adopted during the full-scale testing include (a) brigade-based strategies, (b) community-based strategies and (c) non-water-based strategies. Based on the full-scale tests conducted, it was shown that the water-based strategies outperformed their non-water-based counterparts apart from the dry chemical powder (DCP) fire extinguisher, which demonstrated good suppression performance. The superior suppression performance of the water-based fire protection strategies is attributed to the cooling effect provided through the use of water, which absorbs the heat from the fire and thereby prevents re-ignition from occurring. The tested throwable suppression products failed to suppress the fire and are therefore not suitable for post-flashover enclosure fires. An evaluation matrix is developed to evaluate the efficacy of the tested strategies based on the suppression performance, ease of use, financial feasibility, environmental impact and first response time.

The work continues by developing a numerical model in Fire Dynamics Simulator (FDS) to approximately quantify the amount of water, and discharge rate, required for communities to suppress fires of certain sizes when using a traditional "bucket brigade" technique. The model is calibrated based on the results obtained from the full-scale experiment utilising the bucket brigade approach. Results from the numerical models show that discharge rates of 23 – 40 lpm are suitable for informal settlement fires of approximately 3.85 MW (as produced by a 2.4 x 3.6 m dwelling with a timber fuel load of 25 kg/m²). Communities with water supply points with discharge rate of less than 23 lpm would most likely be unable to suppress fires greater than 3.85 MW in time without resulting in fire spread to adjacent dwellings. Lastly, the influence of a higher fuel load on the suppression duration is investigated, which indicates that the effectiveness of the bucket brigade technique becomes limited for a fire size of 5.77 MW as produced by a 2.4 x 3.6 m dwelling with a timber fuel load of 40 kg/m².

Opsomming

Meer as een miljard mense woon tans wêreldwyd in informele nedersettings. Die toenemende aantal mense wat wêreldwyd in informele nedersettings woon, word toegeskryf aan 'n algehele toename in die wêreldbevolking en 'n toenemende tempo van verstedeliking. Binne die Suid-Afrikaanse konteks is daar 'n onrusbarende toename in die aantal informele nedersettingsbrande sedert die eeuwisseling gedokumenteer, en dit is baie kommerwekkend om te sien hoe min vordering gemaak is met betrekking tot brandveiligheid in hierdie gemeenskappe wat deur armoede getref is. Dit is met hierdie agtergrond dat hierdie werk poog om die gebruik van bestaande aktiewe brandonderdrukkingstelsels vir informele nedersettingbrande te verstaan, in die hoop om die kennis rakende hierdie kwessies te verbeter en sodoende die brandveiligheid in informele nedersettingsgemeenskappe moontlik te verbeter. Die werk bied insig en tegniese leiding vir brandweermanne, munisipaliteite en organisasies wat in informele nedersettings werk en probeer brandveiligheid verbeter.

In hierdie werk word 'n nuwe toetsmetodologie ontwikkel om die onderdrukkingsprestasie van verskillende bestaande brandbeskermingsstrategieë in informele nedersettingbrande te evalueer. 'n Reeks van nege volskaalse eksperimente word uitgevoer op 'n enkele, informele nedersettingwoning met staalbekleding, waartydens die onderdrukking van verskillende brandbeskermingsstrategieë gemeet en ontleed word. Die brandbeskermingsstrategieë wat tydens die volskaalse toetsing aangeneem is, sluit in (a) brandweer-gebaseerde strategieë, (b) gemeenskapsgebaseerde strategieë en (c) nie-water-gebaseerde strategieë. Op grond van die volskaalse toetse, is dit aangetoon dat die watergebaseerde strategieë beter was as hul eweknieë wat nie op water gebaseer is nie, behalwe die brandblusser met droë chemiese poeier (DCP), wat goeie onderdrukkingsprestasie getoon het. Die uitmuntende onderdrukkingsprestasie van die watergebaseerde brandbeskermingsstrategieë word toegeskryf aan die verkoelingseffek wat voorsien word deur die gebruik van water, wat die hitte van die vuur absorbeer en sodoende weerontsteking voorkom. Die getoetsde gooi-onderdrukkingsprodukte kon die vuur nie onderdruk nie en is dus nie geskik vir brande na die opknapping nie. 'n Evalueringsmatriks word ontwikkel om die doeltreffendheid van die getoetsde strategieë te evalueer op grond van die onderdrukkingsprestasie, gemak van gebruik, finansiële uitvoerbaarheid, omgewingsimpak en eerste responstyd.

Die werk word voortgesit deur 'n numeriese model in Fire Dynamics Simulator (FDS) te ontwikkel om die hoeveelheid water en die ontladingstempo te kwantifiseer, wat benodig word vir gemeenskappe om brande van sekere groottes te onderdruk wanneer 'n tradisionele 'emmerbrigade' tegniek gebruik word. Die model is gekalibreer op grond van die resultate wat verkry is uit die volskaalse eksperiment met behulp van die emmerbrigade-benadering. Resultate uit die numeriese modelle toon dat die afvoer van 23 - 40 lpm geskik is vir informele nedersettingsbrande van ongeveer 3.85 MW (soos geproduseer deur 'n huis van 2.4 x 3.6 m met 'n houtbrandstofbelasting van 25 kg/m^2). Gemeenskappe met watervoorsieningspunte met minder as 23 lpm sou waarskynlik nie betyds brande van meer as 3.85 MW kon onderdruk sonder dat brand na aangrensende wonings gelei het nie. Laastens word die invloed van 'n hoër brandstofbelasting op die onderdrukkingstydperk ondersoek, wat daarop dui dat die doeltreffendheid van die emmerbrigadetegniek beperk word vir 'n brandgrootte van 5.77 MW, geproduseer deur 'n huis van 2.4 x 3.6 m met 'n houtbrandstofbelasting van 40 kg/m^2.

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List of abbreviations

AFP	Active fire protection
BNG	Breaking New Ground
CAFS	Compressed Air Foam Systems
CFD	Computational Fluid Dynamics
DCP	Dry chemical powder
EPS	Expanded polystyrene
FDS	Fire Dynamics Simulator
FPASA	Fire Protection Association of South Africa
HRR	Heat release rate
HRRPUA	Heat release rate per unit area
ISD	Informal settlement dwelling
ISO	International Organization for Standardization
LPM	Litres per minute
NAFS	Nozzle Aspirated Foam Systems
NGO	Non-Governmental Organization
PFP	Passive fire protection
RDP	Reconstruction and Development Programme
TSC	Thin-skinned calorimeter

List of symbols

Roman

A_o	Area of opening
A_t	Total surface area of enclosure
b	Width of object
c_p	Specific heat
D	Stick thickness
D^*	Characteristic fire diameter
E	Energy
$E_{coefficient}$	Extinguishing coefficient
g	Gravitational acceleration
h	Height of object
h	Convective heat transfer coefficient
h_c	Crib height
H_o	Height of opening
k	Thermal conductivity of material
l	Length of object
m_o	Initial crib mass
$\dot{m}$	Mass loss rate
$\dot{m_f}''$	Mass burning rate
$\dot{m_{f,0}}''$	Initial mass burning rate
$\dot{m_w}''$	Water mass per unit area
O	Opening factor
P	Pressure
Pr	Prandtl Number
$\dot{q}''$	Net heat flux per unit area
$\dot{Q}$	Heat release rate
Re	Reynolds Number
S	Clear spacing
t	Time

T	Temperature
T_E	Absolute temperature of emitting surface
T_R	Absolute temperature of receiving surface
T_∞	Ambient air temperature

Greek

ΔT	Temperature difference
$\Delta \mathrm{H}_{eff}$	Effective heat of combustion
ε	Emissivity
ρ	Density
ρ_∞	Ambient air density
τ	Shear stress
μ	Viscosity
σ	Stefan Boltzmann constant
ϕ	Configuration factor

Chapter 1: Introduction

1.1. Background to Informal Settlements

Since 1960, Africa has experienced a population boom during which its population has risen from 283 million to a staggering 1.31 billion. In contrast to many European countries, which are projected to experience a population decline by 2050, Africa is currently undergoing the fastest population growth in the world and it has been projected that its population is set to double by 2050 [1]. Along with the rapid population growth, Africa is forecasted to experience substantial urbanisation with an estimated 1.34 billion people set to be living in urban areas by 2050 compared to 541 million people estimated to be living in urban areas in Africa in 2019. With an alarming increase in population accompanied by rapid urbanisation, basic infrastructure and formal housing availability are often insufficient or inadequate, which will result in the growth of existing informal settlements as well as an increasing number of newly formed informal settlements emerging across the continent. As a result, the world will see an alarming increase in the number of people residing in informal settlements.

Informal settlements are residential areas which can formally be defined as an assortment of informal dwellings, which have been constructed on land that has not been formally surveyed or proclaimed for residential purposes by the appropriate authorities [2]. Within the South African context, informal settlements are also referred to as *slums, shantytowns* or *squatter camps* [1]. The informal dwellings within these communities, also known as *shacks,* can be classified as temporary makeshift structures, which are constructed using readily available materials such as wood, corrugated roof sheeting and various plastics, thereby making them inherently susceptible to fires. The choice of materials greatly depends on the geographic location of the informal settlement, since the inhabitants of informal settlements generally suffer from abject poverty and therefore often scavenge the materials required for the construction of their dwellings. As a result, residents are largely reliant on readily available materials within their proximity. The United Nations has associated the following five characteristics with informal settlements [2]:

1. Poorly constructed dwellings
2. Inadequate access to basic services such as electricity and safe running water
3. Lacking security of tenure
4. Limited access to employment opportunities
5. High dwelling densities

Figure 1.1 depicts various dwellings within a typical South African informal settlement.

Figure 1.1: Dwellings within a typical South African informal settlement.

The existence of informal settlements has come about as a direct result of rapid urbanisation. Throughout history people have migrated from rural communities to cities with the prospect of finding job opportunities. Informal settlements provide a home for people that migrate to cities but cannot afford the higher cost of living and therefore resort to living outside of cities in makeshift dwellings on land that has not been proclaimed for residential use. The rate of urbanisation and increase in population within the South African context have surpassed the government's ability to provide land, basic infrastructure and formal housing, which in turn has resulted in the rapid expansion of informal settlements throughout South Africa [5]. Following the downfall of the Apartheid government in 1994, the newly elected government was challenged with the problem of providing people, who were living in informal settlements, with formal housing and access to basic services. This led to the introduction of the Reconstruction & Development Program (RDP) and Breaking New Ground (BNG) program, which were formed to accelerate the delivery of sustainable housing for people living in informal settlements. The objective of the policies was to eradicate informal settlements throughout South Africa by 2014 [6]. According to the national census, in 1996 an estimated 1.5 million households lived in informal dwellings throughout South Africa. In more recent studies conducted in 2001 and 2011 it was found that there was a housing backlog of approximately 3 million and 2.4 million houses, respectively. Between 1994 and 2013 the government has been able to provide 2.7 million households. Therefore, it becomes evident that despite the government's desire to eradicate informal dwellings, the fact remains that the government is not able to produce formal housing at the rate at which it is required.

Fire statistics compiled by the Fire Protection Association of South Africa (FPASA) have shown that South Africa has seen an increase of approximately 67% in the number of reported informal settlement fires between 2003 and 2015 [7]. This data is backed up by an independent study, which concluded that on average, South Africa experiences approximately 10 shack fires a day [8]. The increasing trend of informal settlement fires is of great concern, since it not only impacts the lives of the victims of the affected dwellings (financially as well as socially) but also places an enormous financial burden on the governments and local authorities. Between 2003 and 2015, it has been estimated that the direct average annual costs associated with fighting informal settlement fires in South Africa is approximately R103 million per year [7]. One of the most noteworthy facts is that more than half of the fatalities resulting directly from fires occur in informal settlement communities. In 2015 informal settlement fires accounted for 11.9% of all reported fires in South Africa. However, of the 436 reported fatalities resulting from fires, 219 occurred in informal settlements i.e. 50.2% of all fire-related fatalities. Figure 1.2 illustrates the number of fire-related fatalities per sector, which were reported to authorities in 2015.

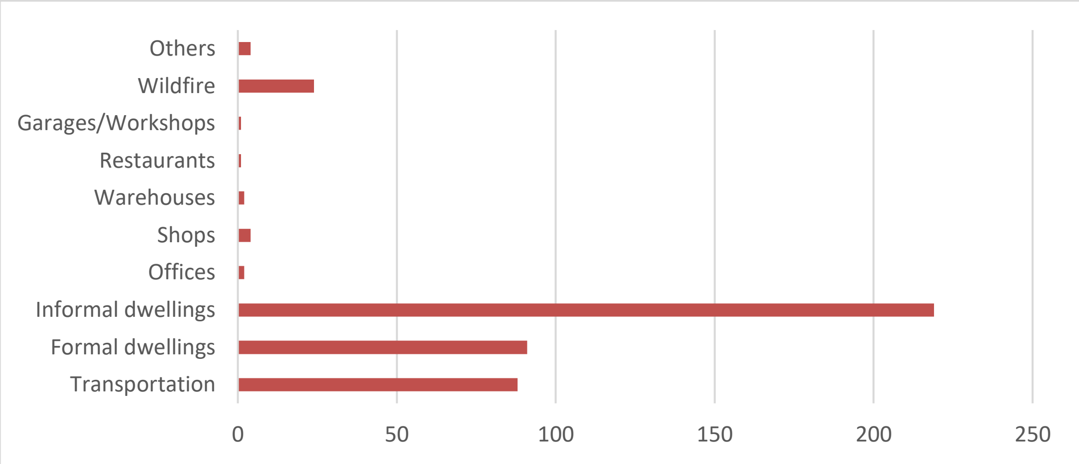

Figure 1.2: South African fire-related fatalities by sector – 2015 [7].

According to an investigation conducted by the Western Cape Disaster Management and Fire Rescue Services, South Africa is estimated to have a fire-related burns mortality rate of 8.5 per 100 000 person [9]. In other words, on average 8.5 out of 100 000 people in South Africa die as a direct result of severe burns resulting from a fire. This is significantly higher than the mortality rate of 6 per 100 000 recorded in other African regions and the global average of 5 per 100 000.

To address the significant problem of fires in informal settlements municipalities, fire brigades, non-governmental organisations (NGOs) and governmental institutions have tried many measures to improve fire safety, often rolling out different kinds of suppression systems.

1.2. Problem Statement

Currently, there is limited research available on the use of different active fire protection systems in the event of informal settlement fires. The development and implementation of *suitable and effective* interventions would assist in improving fire safety within informal settlements. Several concerted efforts have been made to improve fire safety within informal settlement communities, using active fire protection interventions, which includes sprinkler systems, smoke alarms and throwable extinguishing devices [10]. However, these proposed solutions are often developed without, or with limited, technical knowledge of how informal settlement fires behave. Furthermore, the proposed interventions often do not account for socio-economic particularities within these poverty-stricken communities. The success of proposed interventions is partially governed by social factors, which include theft, vandalism, capital and maintenance costs as well as community acceptance i.e. cultural preferences [11].

As a result, many unanswered questions have been raised regarding active fire protection within informal settlement communities, which include: (i) which suppression products are effective at extinguishing post-flashover informal settlement fires, (ii) how much product is required to successfully suppress these fires, (iii) is it possible to model the suppression of informal settlement fires, and (iv) what “standard” should be used for fire safety in an area defined by its lack of standards?

This work aims to provide some insight on these questions, which will enable us to develop more effective solutions with a comprehensive engineering basis.

1.3. Research Goal and Objectives

The primary goal of this research investigation is to develop a core understanding of the performance of various types of suppression systems in post-flashover informal settlement fires through the development of a full-scale experimental benchmark test, along with numerical modelling, in order to potentially improve fire safety within these communities. The research objectives of this investigation are therefore defined as follows:

a) To conduct an extensive literature study which will assist in attaining a greater understanding of fire dynamics, enclosure fires, fire protection strategies and numerical modelling of informal settlement fires.
b) To design and construct an informal dwelling fire test setup, which will serve as an idealized representative structure for the full-scale burn tests.
c) To develop a full-scale testing methodology for benchmarking the performance of various existing active fire suppression systems for post-flashover informal settlement fires.
d) To evaluate and quantify the performance and practicality of selected existing suppression products and systems.
e) To develop numerical models to simulate the response of selected experiments conducted in this research investigation.
f) To conduct a parametric study using numerical models to investigate the effect of various parameters associated with civilian firefighting in informal settlements.

1.4. Project Limitations

The work performed in this thesis forms part of a greater research investigation aimed at understanding the behaviour of informal settlement fires and enhancing fire safety within informal settlement communities. Since, informal settlement fires are still considered a relatively new field of research with many facets, it is necessary to dissect the various aspects associated with such fires into various research projects. Since the inception of the greater research investigation, numerous researchers have studied different aspects of informal settlement fires which includes, but is not limited to, the following:

- Fire loads and burn characteristics of informal dwellings [12].
- Development of standardized experimental testing procedures [13].
- Fire spread throughout informal settlements [14].
- Forensic fire investigations [15].
- Numerical modelling of informal settlement fires [14].

The following points outline the limitations and/or exclusions of the work conducted in this thesis:

i. The scope of this research investigation is explicitly limited to the use of active fire suppression systems. Passive fire protection will form the focus of future work and will not be addressed in this work.
ii. It is not the aim of this research investigation to develop a holistic solution which will solve the problem of informal settlement fires, but rather to test various existing suppression systems and products against an established benchmark test in order to evaluate the effectiveness and practicality thereof.
iii. The suppression systems which are utilized throughout testing are only used once post-flashover conditions have been achieved, since it is relatively simple to suppress fires when they are in the incipient phase, and therefore would not provide an accurate indication of the suppression abilities of the various interventions.
iv. Since informal settlements inherently do not adhere to codes of practice regarding construction products, it is difficult to produce a code for suppression products. Hence, the emphasis in this work is on benchmarking products, rather than having a pass/fail code requirement.
v. Due to the scale of the experiments conducted it was not possible to measure the heat release rate.

1.5. Outline of Research Report

To achieve the objectives outlined in Section 1.3 above, the structure of this thesis is as follows (note that this thesis was completed by the method of publication and that Chapters 3 and 4 are exact copies of papers submitted to the respective journals):

Chapter 1 – Introduction:

The purpose of Chapter 1 is to express the need to conduct this particular investigation. This is achieved by providing relevant background information related to the problem at hand. Additionally, the problem statement as well as the research goals and objectives are formulated.

Chapter 2 – Literature review

Chapter 2 presents an overview of the most important literature which has been reviewed in order to formulate a core understanding of the research discussed and conducted throughout this thesis. The primary fields of research addressed within this chapter include the basic concepts of fire dynamics, science of compartment fires, fire protection strategies and a basic study on numerical modelling of enclosure fires.

Chapter 3 – Development of a full-scale testing methodology for benchmarking fire suppression systems for use in informal settlement dwellings

i. This chapter primarily focuses on the development of a full-scale testing methodology in order to benchmark the performance of various existing active fire protection interventions. The experimental testing procedure which will be adopted throughout this research investigation is discussed.

ii. The representative informal settlement dwelling (ISD) which will be utilized throughout the series of tests is introduced.

iii. Information regarding the sampling of data along with the positioning of the respective data probes is addressed.

iv. The data obtained from the full-scale burn tests will be summarised, evaluated and discussed in this chapter. The various fire protection strategies which were implemented during the full-scale burn tests are assessed based on their performance and practicality by considering socio-economic factors.

Chapter 4 – Numerical modelling of water application rates for post-flashover informal settlement fires

i. Chapter 4 is set to validate the results obtained from selected full-scale burn tests by means of Computational Fluid Dynamics (CFD) modelling. The results obtained from the numerical model are compared against those obtained from the full-scale tests.

ii. Both sets of data are critically analysed, and any discrepancies are discussed.

iii. A parametric study is conducted examining the extinguishing performance of various water application rates on fires of various sizes.

Chapter 5 – Conclusion and recommendations

A brief overview of the research project is presented in the final chapter. Key findings and the importance thereof are addressed along with recommendations for future research and the feasibility of the suppression systems and products covered throughout this research investigation.

The structure of the thesis is visually depicted in Figure 1.3, which provides an outline for the flow of the work covered in this thesis, as well as potential areas of interest for future work.

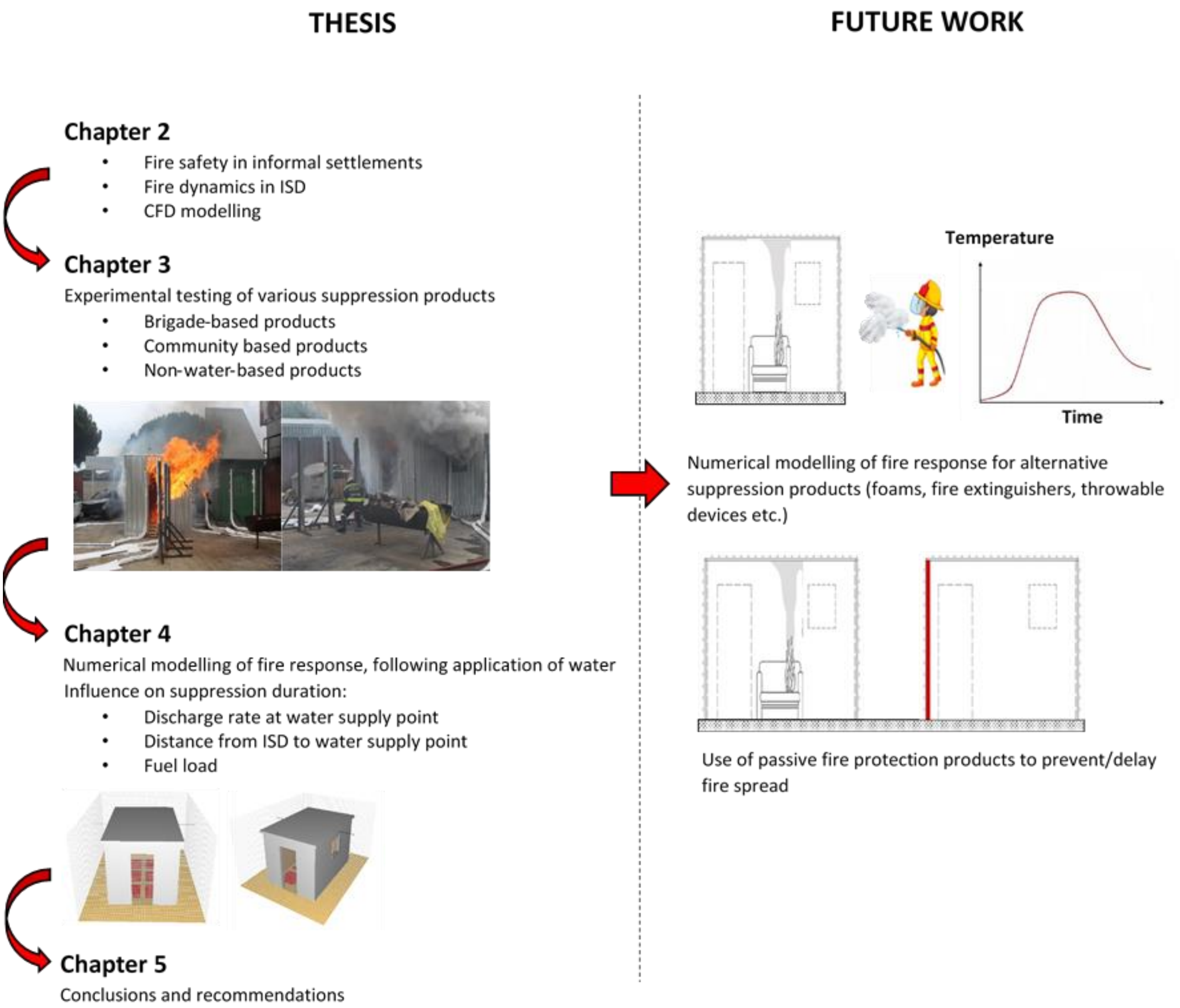

Figure 1.3: Research investigation outline including potential future work.

Since this thesis is written in the form of publications, it is necessary to introduce the issue at hand as well as a brief literature review at the beginning of Chapters 3 and 4. Therefore, some information may be repeated in subsequent chapters.

1.6. References

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Chapter 2: Literature Review

2.1. Introduction

This chapter aims to provide the reader with the most important information required to develop a core understanding of compartment fires and informal settlement fires, thereby equipping the reader with the knowledge required to understand the remaining chapters. This section commences by introducing and defining several key principles of fire safety, fire dynamics and enclosure fires, which include, but are not limited to, the combustion process, modes of heat transfer, stages of fire development etc. Thereafter, a brief discussion of active and passive fire protection will be presented, which includes a general overview of selected active fire protection strategies and products that are utilised in Chapter 3. The chapter concludes by briefly discussing the fundamental concepts of simulating enclosure fires through numerical modelling, as will be employed in Chapter 4.

2.2. Fire Safety

The primary goal of fire safety is to reduce the probability and severity of injury, damage and death during the event of a fire to a level which is deemed acceptable [1]. Several approaches have been identified which can be adopted to improve fire safety within communities [2]:

- Mitigation - Measures which can be taken to prevent or reduce the probability and severity of the consequences of a fire.
- Preparation - Strategies, procedures and training which are to be followed in the event of a fire.
- Response - Actions and decisions made amidst a fire with the intent to save lives, protect properties and possessions.
- Recovery - Actions and decisions made after the fire with the purpose of providing necessary healthcare and treatment and improving the fire safety.

Figure 2.1 summarizes the various approaches along with twelve key aspects of fire safety, which has been developed by Arup, based on the Disaster Life Cycle approach [2]. In terms of this research investigation the focus will be on the response i.e. the decisions and actions taken during a fire which will assist in reducing the probability and severity of injury, damage and death.

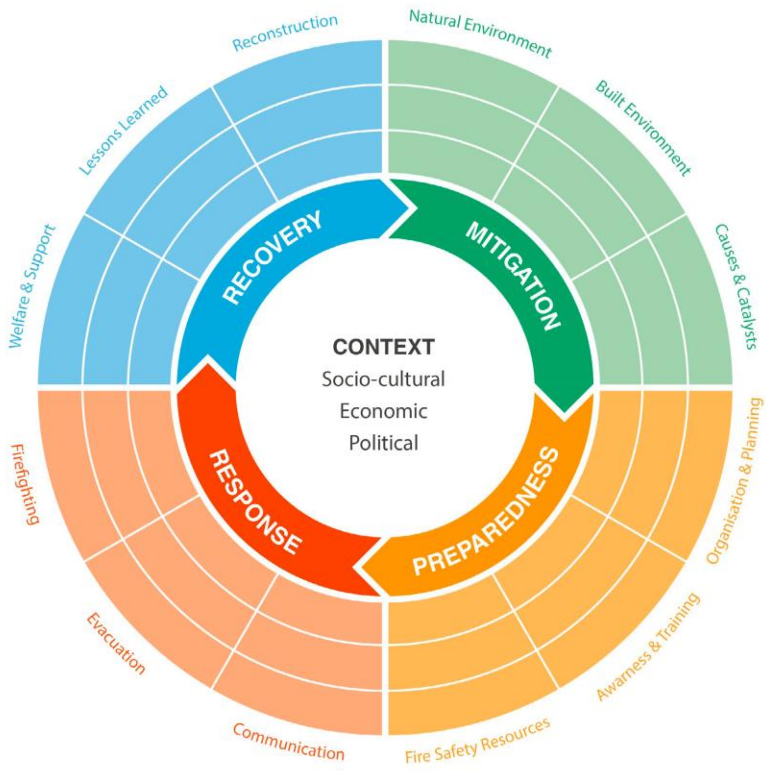

Figure 2.1: Approaches and aspects of fire safety [2].

However, when discussing the issue of fire safety, it is important to distinguish between the various objectives of fire safety during the different stages of a fire. It is key to distinguish between the objectives of fire safety pre- and post-flashover (as discussed below). During the incipient phase of a fire the main objective of fire safety is to protect the lives of occupants of the affected structures/dwellings and evacuate them to a point of safety. When the fire transitions into a fully-developed fire the objectives of fire safety change and the main objectives shift to ensure the safety of the firefighters and to guarantee the structural integrity of the structure itself as well as the surrounding structures [3][4]. A detailed explanation pertaining to the various stages of an enclosure fire is provided in Section 2.3.3.2.

2.3. Fire Dynamics

Fire has played an integral role within societies since the earliest times of mankind, and it possesses the potential to act as a great source of power and heat which can be harnessed to benefit society on a large scale [4]. However, when fires manage to escape the confinements of human control, they possess the ability to endanger lives and cause catastrophic material damage. Fires are a dominant source of energy, especially in low income areas such as informal settlements, where they serve as a source of energy for cooking, cleaning and heating purposes. Although the benefits of fires have been harnessed and valued for thousands of years, upon closer inspection it becomes evident that the science behind fire dynamics is often misunderstood due to the unpredictable and complex nature thereof.

2.3.1. Combustion

Fire can be regarded as the manifestation of combustion, during which a material is rapidly oxidised in an exothermic redox reaction, thereby releasing light, heat and other reaction products [5]. The combustion process can only occur under a certain set of conditions which requires a well-proportioned mixture of fuel, oxidant as well as the presence of heat and the unhindered ability to undergo the chemical redox reaction [3]. The relationship and interaction of the fuel, oxidant, heat and chain reaction are required to successfully sustain a fire from the point of ignition. This relationship is commonly illustrated in the form of a *fire triangle* or alternatively *fire tetrahedron* if the chain reaction is considered. A schematic illustration of the various components of the fire triangle is depicted in Figure 2.2.

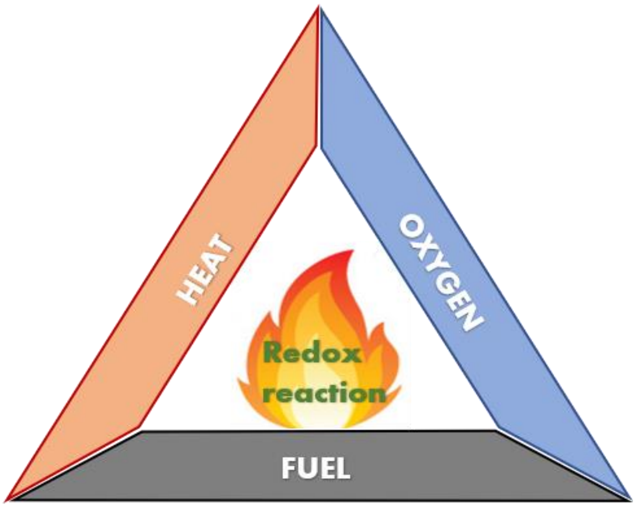

Figure 2.2: Fire Triangle.

The combustion process can only occur if the fuel for the fire is present in a gaseous state. In the case of liquid fuels, the ambient temperature of the fuel simply needs to be raised to its evaporation temperature, at which point the fuel will transform from a liquid state to a gaseous state. However, the process of transforming a fuel to a gaseous state is somewhat more complex for solid fuels. For solid fuels to burn, it is first necessary for them to undergo an endothermic chemical decomposition known as *pyrolysis* which in turn consists of a series of complex reactions [6]. During the pyrolysis procedure, volatile particles are formed near the surface of the solid which are then able to enter the flame and form the gaseous fuel required for the combustion process [4]. This requires substantially more energy than the evaporation process of liquid fuels and therefore the required surface temperatures for the ignition of solids typically tends to be around 400 ^{o}C (subject to the material properties of the fuel type).

The proportion of fuel to oxygen plays a significant role in the combustion process and the development of the fire. The supply of oxygen is directly proportional to the rate of energy released within a compartment [3]. A fire is said to be either *fuel-controlled* or *ventilation-controlled.* In the case where a fire is said to be fuel-controlled, the growth and spread of the fire is explicitly limited by the characteristics of the combustion materials (amount of fuel, exposed surface area, density, heat of combustion etc.). During the incipient stage of a fire, i.e. shortly after the time of ignition, the fire is fuel-controlled since there is an abundance of oxygen available for the complete combustion of the fuel. It is possible for a fire to become ventilation-controlled, during which incomplete combustion of the fuel occurs, due to oxygen deficiency. This typically occurs during the fully-developed stage of a fire. However, a fire does not necessarily have to reach a point where it changes from a fuel-controlled to a ventilation-controlled fire. This depends entirely on the ventilation conditions of the compartment, and the availability of fuel, and will be addressed in more detail in Section 2.3.3.2.

The abovementioned combustion process can either result in the development of a *smouldering fire* or a *flaming fire,* each having a unique set of characteristics. The former is a slow and flameless form of combustion which occurs at low temperatures and possesses a low heat release rate (HRR) [7]. Smouldering fires are the leading cause of death in residential fires due to the toxic nature of the resulting combustion gases [8]. Carbon monoxide, *CO,* is emitted during the smouldering combustion process which can be life threatening for the occupants of a dwelling and can ultimately result in death by asphyxiation. This is a major problem in informal settlement dwellings, which contain mattresses and furniture constructed from materials which promote smouldering fires. Candles and glimmering cigarette buds account for the main ignition sources of smouldering fires in informal settlement dwellings [9]. Due to the small geometry of informal settlement dwellings (ISD), combined with the toxic nature of the carbon monoxide released during a smouldering fire, it is vital for occupants to escape the enclosure immediately to avoid potential death by asphyxiation.

A flaming fire on the other hand refers to a rapid form of combustion which concurrently possesses a high energy release rate. This occurs when the fuel and the oxidant are in the same phase i.e. both agents are present in a gaseous state. Visible flames and high temperatures are some of the characteristics associated with flaming fires.

2.3.2. Heat Transfer

Heat is a by-product which is released during the combustion process and it is transferred from one form of matter to other matter by the three principle mechanisms of heat transfer, namely:

1. Convection
2. Conduction
3. Radiation

These three mechanisms of heat transfer are responsible for the flow of energy within a system and are illustrated in Figure 2.3 below. The basic principles are addressed in further detail in the following subsections. For the purpose of this investigation it is only required to have a basic understanding of the three modes of heat transfer and therefore the three concepts of heat transfer will not be discussed in great detail. For more information pertaining to the modes of heat transfer the reader is referred to [1,3,4].

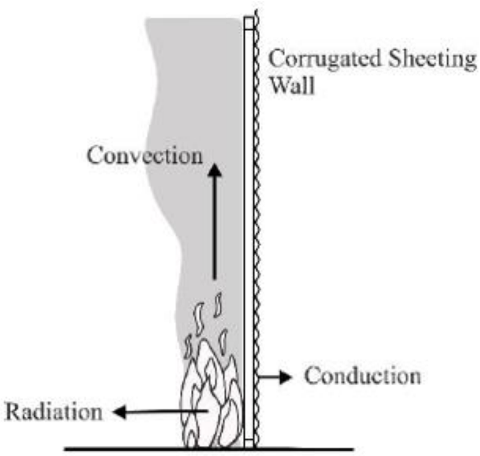

Figure 2.3: Modes of heat transfer [10].

2.3.2.1. Convection

Convection is the mode of heat transfer which arises due to the movement of a fluid (liquid or gas) over a surrounding solid object [1]. Convective heat transfer is driven by the buoyant flow of gases within a compartment and is predominantly responsible for the upward flow of heat to the ceiling level within a compartment. In addition to the influence on the upward flow of heat to the ceiling, convection is also largely responsible for heat escaping the enclosure through compartment openings. The amount of convective heat transfer can be quantified by means of Equation 2.1:

$$\dot{q}'' = h\Delta T \tag{2.1}$$

where $\dot{q}''$ is the net heat flux per unit area, h is the convective heat transfer coefficient and ΔT is the temperature difference between the solid object and the fluid flowing over it. Convection is the dominant mode of heat transfer during the incipient phase of a fire due to the upward flow of the heat produced from the combustion reaction.

2.3.2.2. Conduction

Conduction is the mechanism of heat transfer which is exclusively associated with solid objects. Heat within a solid is transferred from an area of high temperature to an area with a lower temperature. This transfer of energy is achieved by means of free electrons within the solid material [4]. Research has shown that materials which have been proven to be good electrical conductors generally also act as good thermal conductors. Figure 2.4 provides a visual illustration of the principle of conduction for the case of one-dimensional steady state conduction.

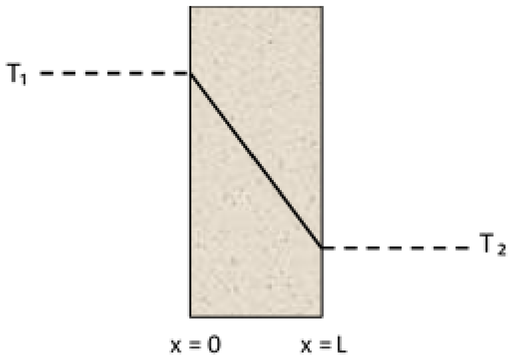

Figure 2.4: Principle of conduction and temperature gradient.

The amount of conductive heat transferred from the area of high temperature to the area with a lower temperature can be quantified by means of Equation 2.2:

$$\dot{q}_x'' = \frac{k}{L}(T_1 - T_2) \tag{2.2}$$

where $\dot{q}_x''$ is the heat flux per unit area in the direction of heat flow, L is the distance between the two points of interest, T_1 and T_2 are the measured temperatures at the two points of interest, and k is the thermal conductivity of the material, which governs the rate of heat transfer through the respective material.

2.3.2.3. Radiation

The mode of heat transfer where heat is transferred by means of electromagnetic waves is known as radiation. Radiation is the only mechanism of heat transfer that does not require an intervening medium, since the electromagnetic waves can travel through liquids, solids as well as a vacuum [1]. Radiation becomes the most dominant mode of heat transfer as the temperature of the fire increases

[1]. The heat from the heat source can be absorbed, transmitted or reflected to any surrounding combustible materials within the compartment. Subsequently, radiation to a large extent governs the growth and spread of fires within an enclosure. The amount of radiative heat projected upon the receiving object is given by Equation 2.3:

$$\dot{q}'' = \emptyset \varepsilon \sigma \left({T_e}^4 - {T_r}^4 \right) \tag{2.3}$$

where Ø is a configuration factor, which accounts for the geometric relationship between the surfaces of the emitter and the receiver, σ is the Stefan Boltzmann constant ($5.67 \times 10^{-8}\ W/_{m^2K^4}$), ε is the emissivity constant (ε=1 for a perfect emitter), T_e and T_r are the absolute temperatures of the emitting and receiving surfaces respectively.

2.3.3. Compartment Fires

2.3.3.1. Factors influencing compartment fires

The behaviour of compartment fires differs from that of wildfires, due to various factors which can be divided into two distinct categories, namely those associated with the compartment itself and those associated with the fuel within the enclosure. Some of these factors which have been identified by [3] include:

- Ignition source
- Fuel
- Compartment geometry
- Ventilation

The factors listed above will be discussed in more detail to gain a better understanding of how these factors influence the overall behaviour of compartment fires. The following information was sourced from [3] unless stated otherwise.

Ignition Source: The ignition source plays a significant role in the development of the fire within the compartment itself. For example, the source of ignition can either be electrical, mechanical or chemical, each emitting a different amount of energy. The greater the energy emitted from the ignition source, the greater the potential for a rapid fire growth within the compartment. This is a common problem in informal settlement dwellings which utilize a variety of energy sources for different tasks, which are often unsafe and potentially dangerous forms of energy. A study conducted by Pharoah *et al.* found that it is common for occupants of informal settlement dwellings to use candles for lighting, firewood for heating and paraffin for cooking and hygienic purposes [11]. All these energy sources pose a potential hazard if left unattended.

Fuel: It might seem apparent but one of the primary contributors which predetermines the fire growth within an enclosure is the fuel within the compartment. Aspects of the fuel which influence the development of fires within enclosures include the type and amount of fuel present, the positioning, orientation, and spacing of the fuel load as well as the exposed surface area of the fuel load.

The type of fuel situated within a compartment is typically dependent on the class of occupancy of the structure. For example, the type of combustible materials found in a building will differ for structures intended for residential purposes opposed to those utilized for industrial operations. Furthermore, the type of fuel contained within a compartment is also area dependent. For example, the type of fuels found within low-income residential dwellings will differ significantly to those found in high-income residential homes. The net calorific value, also known as the heat of combustion, is one of the most important factors associated with the fire safety of materials. The calorific value of a material refers to the amount of energy that is released during the complete combustion thereof [1]. The greater the calorific value of a substance, the more energy is released during the combustion process. The net calorific values of materials which are commonly found within informal settlement dwellings are listed in Table 2.1.

Table 2.1: Net calorific values for common informal dwelling objects [1]

Material	Calorific Value [MJ/kg]
Solid materials	
Wood	17.5
Clothes	20
Cotton	20
Paper	18.4
Coal	30
Rubber	30
Leather	16.8
Cardboard	16.9
Chemicals	
Alcohol	30
Gasoline, Petroleum, Diesel	45
Paraffin	43.3

The density of the combustible material will influence the development of fire growth, since dense materials typically result in a slow fire growth but burn for a prolonged period. Lighter, more porous materials on the other hand tend to burn for a shorter period at a higher intensity, which poses a higher threat in terms of human evacuation.

A further factor which influences the propagation of fire in enclosed areas is the positioning of the fuel source. For example, a fuel package located in a corner of an enclosure or along one wall will result in an accelerated flame spread within the compartment, as opposed to the case where the fuel package is located in the centre of the room, away from the compartment boundaries. This phenomenon is illustrated in Figure 2.5 from which it can be observed that the location of the fuel package plays a substantial role in terms of fire development. It should be noted that the temperatures measured when the fuel package is located in the corner of a compartment are significantly greater than when the fuel package is situated in the centre of the enclosure i.e. away from the compartment boundaries. This is primarily attributed to the entrainment of cool air into the fire plume for the latter case, and thermal feedback from walls in the former.

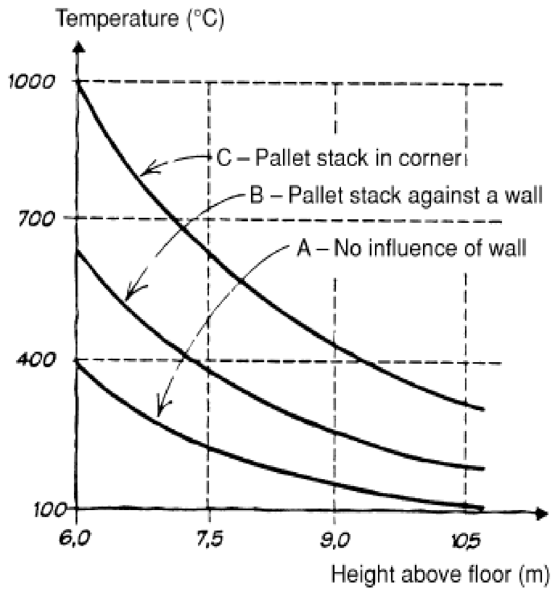

Figure 2.5: Influence of fuel location on the temperature of fire plume [3].

The spacing of the fuel packages is the last factor that will be discussed in this section. Fuel packages which are spaced closely to one another will result in a faster fire spread. This arises, since the heat transfer among the individual fuel packages is more concentrated, thereby resulting in a reduced time for the adjacent fuel package to reach its ignition temperature.

Compartment Geometry: When considering a burning fuel package, the hot gases which are emitted from the combustion process rise to the top of the compartment due to buoyancy forces. This leads to the formation of a hot layer at the ceiling level, which descends further towards the bottom of the compartment as more hot gases are emitted. The hot layer radiates heat back towards the fuel packages, which in turn intensifies the combustion process. This process is known as *thermal feedback* and it is repeated until the hot air manages to escape the confines of the enclosure or when the fuel within the compartment has been depleted. Therefore, it becomes evident that the compartment geometry plays a substantial role in terms of the thermal feedback experienced within the enclosure. An enclosure with a low ceiling and fuel packages spread evenly along its floor will experience much higher temperatures and a rapid-fire growth compared to the same enclosure with a higher ceiling, due to the increased thermal feedback to the fuel.

Ventilation Conditions: The availability of oxygen within a compartment is one of the three crucial components of the fire triangle as discussed in Section 2.3.1. When flaming combustion conditions have been achieved and the fire is ventilation-controlled, it is necessary for the fire to have enough oxygen for the fire to develop further. This is largely governed by the compartment openings such as the windows and doors situated within an enclosure. The size, position and shape of the openings all influence the amount of oxygen entering the compartment, and therefore impact the growth of the fire during the fully developed stage. The effect of an opening has been quantified by Karlsson and Quintiere [3] using Equation 2.4, known as the opening factor:

$$O = \frac{A_0\sqrt{H_0}}{A_t} \tag{2.4}$$

O – Opening factor $[m^{0.5}]$

A_0 – Area of opening [m²]

H_0 – Height of opening [m]

A_t – Total surface area of enclosure [m²]

Equation 2.4 is only valid for compartments that contain a single opening. For compartments containing multiple openings, such as the compartment illustrated in Figure 2.6, the following equations have been altered by Buchanan and Abu [1] in order to make them compatible with Equation 2.4.

$$H_0 = \frac{A_1h_1 + A_2h_2 + \cdots + A_6h_6}{A_0} \tag{2.5}$$

$$A_0 = bh_1 + b_2h_2 + \cdots + b_6h_6 \tag{2.6}$$

$$A_t = 2(l_1l_2 + l_1l_3 + l_2l_3) \tag{2.7}$$

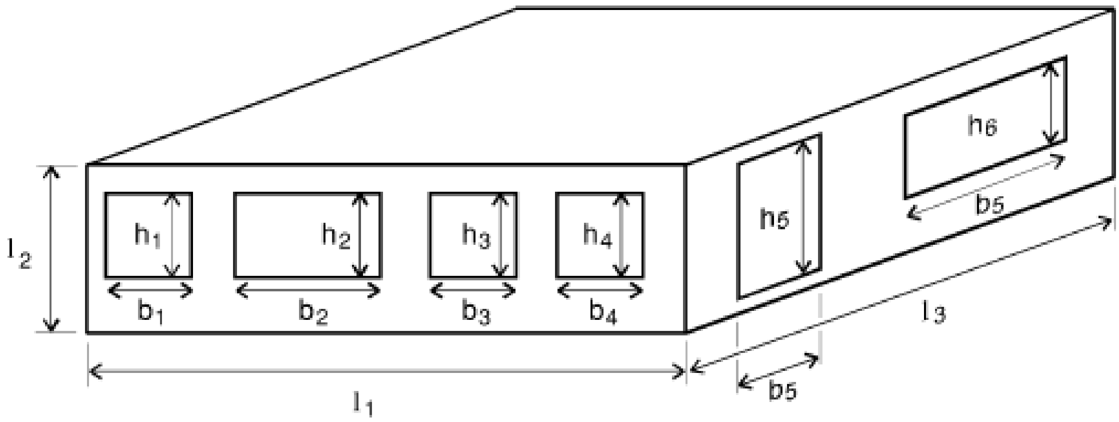

Figure 2.6: Opening factor for compartments with several openings [3].

When considering a compartment fire which is ventilation-controlled, a high value for the opening factor will yield a more intense burning rate within the compartment, since more oxygen is able to enter through the compartment openings and fuel the combustion reaction [1].

2.3.3.2. Stages of compartment fires

Extensive research into the behaviour of enclosure fires has been conducted by Pettersson *et al.* with a special focus on the development of compartment fires [12]. The development of fires within informal settlement dwellings closely resembles that of an enclosure fire. Karlsson and Quintiere [3] identified five key phases associated with enclosure fires, namely:

1. Ignition
2. Growth
3. Flashover
4. Fully developed fire
5. Decay

These five phases are depicted in Figure 2.7, which illustrates the time-temperature relationship of a typical enclosure fire, throughout the various phases. For a detailed discussion on fire dynamics in informal settlements refer to Cicione et al [13–15].

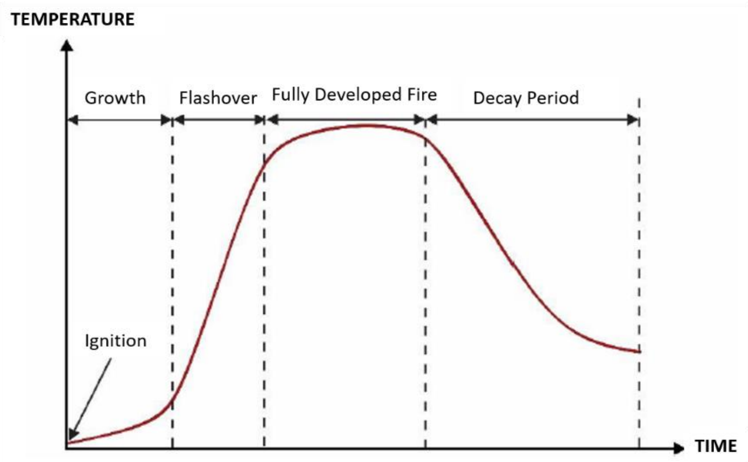

Figure 2.7: Phases of a compartment fire [12].

Ignition signifies the start of the combustion process and occurs when the ambient temperature of the combustible material is elevated to a point beyond its ignition temperature. At this point, the compartment has a negligible influence on the development of the fire, and therefore the fire is fuel-controlled [3]. Ignition can be induced in one of two manners, namely, through *piloted ignition* or *spontaneous combustion*. Piloted ignition refers to the ignition of a combustible substance which results from being directly exposed to a high external energy source, such as a flame or a spark [16]. Spontaneous combustion on the other hand, also known as auto-ignition, occurs when the ambient temperature of a combustible material is elevated to a point at which it will ignite without coming into direct contact with an external flame or spark. Piloted ignition typically occurs at a temperature ranging from 250-450 ^{0}C, whereas the temperature required for auto-ignition usually requires a surface temperature of at least 500 ^{0}C [3]. The ignition temperatures of selected items which are typically found within or around informal settlement dwellings are listed in Table 2.2 [17].

Table 2.2: Ignition temperatures of common informal dwelling objects [17].

Material	Ignition Temperature (°C)
Solids:	
Paper	218 – 246
Leather	212
Coal	400 -500
Wool	228 – 230
Cotton	250
Rubber	260 – 316
Nylons	424 – 532
Liquids:	
Kerosene	229
Gasoline	257
Diesel	399
Alcohol	365
White spirits	232
Paint thinners	245
Gases	
Propane	466
Butane	405

The **growth phase** or the *initial flame spread* phase of an enclosure fire follows after successful ignition. During this phase it will be established whether a smouldering or a flaming fire will develop. The rate of fire growth is dependent on various factors, such as the type of fuel present in the compartment, type of combustion and the amount of oxygen available as discussed in Section 2.3.3.1. During this phase the fire continues to be fuel-controlled, since there is a surplus of oxygen available within the compartment required for the combustion process. The main characteristic of the growth phase is the increasing energy release rate or heat release rate (HRR). The HRR refers to the amount of energy released from the combustible material within the enclosure over a certain amount of time [3]. The hot gases which are released within the enclosure as by-products from the combustion reaction begin to fill the enclosure. These combustion gases rise to the ceiling of the enclosure due to buoyancy forces and result in the formation of a hot layer.

Flashover refers to the phase of a compartment fire during which the fire transitions from the growth phase to the fully-developed phase. The flashover period of a fire can formally be defined as the rapid transition from localized burning of fuel packages within the compartment, to full room involvement of all combustible materials [18]. As the fire continues to develop during the growth phase it releases additional hot combustion gases which in turn results in the expansion of the hot layer at ceiling level, which descends further down the compartment as more combustion gases are released. A significant temperature increase within the compartment ensues, since the hot combustion gases descend into the cold layer and radiate heat onto the surfaces of the directly exposed combustible materials. If the heat radiated towards the fuel package heats the material beyond its auto-ignition temperature, it will cause the fuel to ignite spontaneously. The phenomenon of flashover does not occur at a specific point but is dependent on numerous factors such as the thermal properties of the fuel sources, fuel orientation and position, as well as the enclosure geometry. Karlsson and Quintiere [3] identified the following factors which predominantly enable flashover to occur:

- The fire occurs in an enclosure with sufficient ventilation and fuel.
- The enclosure should not allow the hot combustion gases to escape at ceiling level.
- The temperature within the enclosure should reach 500 – 600^{0}C or the radiation experienced at ground level should be in the vicinity of 15 – 20 kW/m^2.

After flashover has occurred the fire is said to be fully developed. This signifies the penultimate phase of an enclosure fire and is simply referred to as a *fully-developed fire* or *post-flashover fire*. Typically, the temperatures encountered within the compartment during this period range between 700 – 1200 ^{0}C. During this phase the fire attains its peak HRR and is predominantly ventilation-controlled, since the combustion reaction is limited by the amount of oxygen entering through the compartment openings. The fully-developed phase of a fire is potentially the most dangerous in terms of human survival and fire spread, since the fire is mostly ventilation-controlled, which in turn results in the production of unburnt gases. These unburnt gases accumulate within the enclosure, however, if they manage to escape the enclosure by means of an opening, they mix with oxygen rich air and form a combustible gas mixture, which will ignite if exposed to temperatures above its auto-ignition temperature, resulting in a visible flame emerging from the compartment opening [19].

Decay is the final phase associated with compartment fires and occurs once the fuel within the compartment has been expended. The fully developed fire cannot be sustained, thereby resulting in a reduction of the HRR, which in turn causes a rapid decline of the average temperature experienced in the enclosure. During the decay phase the fire becomes fuel-controlled once more.

When considering the five different phases of an enclosure fire it becomes evident that the compartment geometry as well as the fuel properties play a significant role in terms of the fire development. With regards to this research investigation, the focus will be directed towards the post-flashover behaviour of compartment fires, since the primary goal is to investigate the suppression ability of various active fire protection interventions for fully-developed compartment fires.

2.4. Fire Protection

The following section gives an overview of various suppression techniques that are utilised in Chapter 3, highlighting what could be considered for combatting informal settlement fires. Details below are in excess of the summary provided in Chapter 3. Fires are typically categorized into one of five distinct classes, based on the properties of the combustible materials. The classification of fires and the associated fire development and suppression characteristics is addressed in Section 3.3.3.

The primary objective of fire protection in the built environment is to enhance fire safety within communities by protecting life and subsequently minimising the effects of fires on properties and material belongings as well as the surrounding environment. Enhanced fire protection can be achieved through the selection of construction materials, structural layout, insulation materials and suppression products. Fire protection methodologies are commonly categorized into two primary categories, namely active fire protection (AFP) and passive fire protection (PFP).

Fire suppression is achieved by targeting the four components which allow for the combustion process to be sustained as discussed in Section 2.3. Fire protection products or systems, therefore, aim to extinguish a fire in one of the four following manners:

1. **Cooling** – Removal of heat thereby lowering the temperature required for the combustion reaction.
2. **Smothering –** Separation of fuel packages from the oxygen required for the combustion process
3. **Starvation –** Removal or separation of fuel packages from the burning environment.
4. **Inhibition –** Disruption of the chemical chain reaction.

2.4.1. Active Fire Protection

Active fire protection refers to fire protection methodologies, which are designed to intervene in the event of a fire either by manual or automatic activation, where the automatic activation is often managed by a network of sensors [20]. AFP seeks to suppress fires and is generally supplied in the form of fire detectors and alarms, mobile fire extinguishers, sprinkler systems and smoke management systems.

2.4.1.1. Water

Using water as an extinguishing medium is possibly the most common manner of extinguishing fires and it is so ubiquitous that mankind has a basic understanding of how water functions as an extinguishing agent. However, upon closer examination it becomes apparent that the use of water as an extinguishing medium is more complex than initially anticipated. The use of water as an extinguishing agent may prove to be undesirable under certain circumstances, for instance in the event of a fire which involves hydrocarbons such as gasoline, alcohol, oil etc., since the fuel floats on the water surface due to the lower density compared to that of water. A burning layer or film is formed on top of the water which can aggravate the situation, since the burning fuel is able to spread along the surface of the water. A further scenario in which the use of water as a suppression agent is undesirable arises in the event of an electrical fire, since the water would function as an electrical conductor, thereby posing a serious hazard to occupants. Water can, therefore, only be utilized for Class A fires which involve organic combustible solids such as wood, cardboard, paper etc.

Extensive research has been carried out to identify and characterize the effect and behaviour of water as an extinguishing agent [21]. It has been identified that a water stream which is broken down into numerous small water droplets is more effective at lowering the heat as compared to a continuous solid water stream. This may be attributed to the higher total surface area of the water particles in the broken-down stream compared to that of a solid stream. The broken-down stream is therefore able to absorb significantly more heat, since the droplets vaporize more rapidly [21].

When attempting to suppress a compartment fire with water it is necessary to determine the critical rate of flow, which is commonly defined as the water flow required to lower the temperature of the combustible material within a compartment to a point where it no longer emits combustion gases. A crude method used by firefighters to quickly estimate the critical rate of flow is the *Iowa-formula* expressed in Equation 2.8 below.

$$Required\ flow = [l\ \times b\ \times h] \times \frac{4}{3}\ [lpm] \tag{2.8}$$

l – length of the compartment [m]

b – width of the compartment [m]

h – height of the compartment [m]

The function of water as an extinguishing medium will be further addressed in Chapter 3.

2.4.1.2. Dry Chemical Powder Fire Extinguishers

Dry chemical powder (DCP) fire extinguishers are arguably the most commonly utilised non-water-based active fire protection device and are suitable for Class A, B and C fires. The cylinder of the fire extinguisher contains two key substances, namely an extinguishing agent and a propellant. The propellant is a chemical stored under pressurized conditions and ensures that the extinguishing agent is dispersed when the trigger valve of the extinguisher is depressed [22]. Figure 2.8 depicts a typical mobile DCP fire extinguisher.

Figure 2.8: Dry chemical powder (DCP) fire extinguisher [23].

As previously mentioned, DCP fire extinguishers are effective at suppressing Class A, B and C fires, however, the extinguishing mechanism for the various classes differ. The monoammonium phosphate powder contained within the mobile fire extinguisher has been fluidized and siliconized during the manufacturing process to enhance the flowability of the powder and prevent it from forming clumps when exposed to elevated temperatures [22]. In the event of a Class A fire the extinguishing agent is directed towards the fire where it melts at approximately 175 – 205 ^{o}C. As the monoammonium phosphate powder melts it forms an insulated layer over the fuel, thereby separating the fuel from any available oxygen. For Class B fires, the extinguishing agent disrupts the chemical reaction required for the combustion process by displacing the oxygen required to sustain the combustion reaction, consequently smothering the fire. The extinguishing agent blankets the fuel and prevents the combustion gases from escaping, thereby knocking the fire. The function of the extinguishing agent for Class C fires is similar to that of Class A fires, since the powder coats the fuel and extinguishes the fire. The monoammonium phosphate powder is a non-conductor of electricity therefore making it a safe and effective extinguishing product, since it will not conduct the energy back to the operator of the mobile fire extinguisher. The use of DCP fire extinguishers in post-flashover Class A fires will be addressed in more detail in Chapter 3.

2.4.1.3. Compressed Air Foam Systems

Compressed Air Foam Systems (CAFS) were initially developed in the 1930’s and are used in the firefighting industry to suppress large fires by supplying a firefighting foam solution under pressurized conditions to the fire. CAF systems function by providing a constant stream of water which is mixed with a foaming agent and pressurized air. This mixture can be directed towards a fire from a safe distance due to the pressurized nature of the stream. A CAF system essentially comprises of a water source, centrifugal pump, foam concentrate tanks, air compressor, mixing chambers and a control system which regulates the proportioning of the air, foaming agent and water. Laskaris and Sulmone have shown through experimental research that CAFS are effective at extinguishing Class A as well as Class B fires [24]. With reference to Figure 2.9, CAF systems essentially function in the following sequence:

1. Water from a nearby source (e.g. fire truck or fire hydrant) is introduced to the CAF unit by means of a water inlet pipe or hose line.
2. Water is directed along the water flow path towards the water and foam chemical mixing unit, where a controlled amount of foaming agent is added to the water stream, thereby producing the desired foam solution.
3. Air is introduced into the foam solution by means of an air discharge check valve from the air compressor.
4. The compressed air foam is directed towards the hose lines, which are then used to distribute the compressed air foam mixture towards the fire.

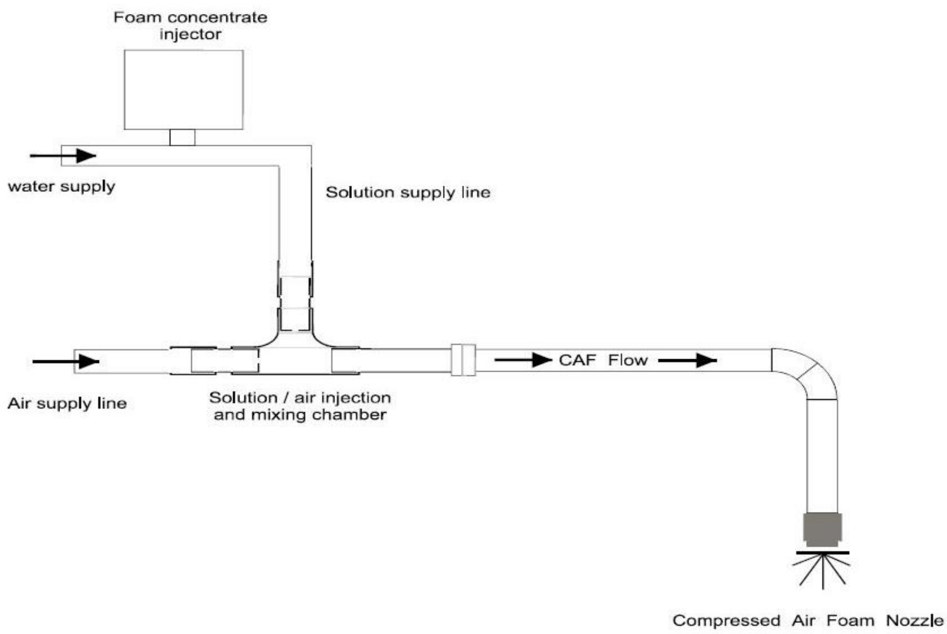

Figure 2.9: Compressed air foam (CAF) system [25].

The efficiency of CAFS is dependent on the quality the firefighting foam. It is therefore vital to ensure that the air and the foaming agent are mixed and added at the required proportions. A compressed air foam mixture which contains a high ratio of foaming agent will result in a solution with a lower fire extinguishing quality, since the flowability of the mixture is reduced due to the increased foam viscosity [24]. Additionally, a high foaming agent ratio increases the cost of the CAF mixture and the frequency at which the foaming agent needs to be replenished. Information from the literature and product specifications show that the proportion of foaming agent within CAF systems typically range from 0.3 – 1.0% for Class A and Class B fires [26][27].

The introduction of the air to the foam solution similarly influences the quality of the resulting CAF mixture. The amount of air introduced into the foam solution impacts the consistency of the CAF mixture. An insufficient quantity of air to the foam solution results in a CAF mixture which is too watery and will not extinguish a fire as effectively, since the foam will not contain large air bubbles which are essential for the formation of a protective layer that shields the combustible material from the incident radiant energy and flames. On the other hand, an excessive amount of air will result in a mixture which is too dry and could potentially have severe repercussions, since the air could cause extreme surging of the hose lines which consequently could injure firefighters in close proximity of the hose line. It is important to take note that the air may not be introduced to the water in the absence of the foaming agent, since water and air do not mix under pressure. Chapter 3 addresses the utilization of CAF systems for Class A post-flashover fires and the suppression characteristics thereof.

2.4.1.4. Nozzle Aspirated Foam Systems

In contrast to CAFS, nozzle aspirated foam systems (NAFS) utilize two, instead of three, pumping systems. This arises due to the absence of the air compressor which is required for CAFS. Therefore, NAFS simply have to combine two pumping systems, namely one pumping system which is responsible for the water supply and another pumping system which functions as the foam pump/proportioner. Similarly, as for CAFS, the proportioner is accountable for ensuring that the correct proportion of foam concentrate is added to the water in order to produce the desired percentage of foam solution [28].

For NAFS, the air required for the formation of the foam bubbles is introduced and agitated into the foam solution by means of the nozzle head. With regards to Figure 2.10, it can be seen how air is introduced into the foam solution through the design of the nozzle head. The air is able to entrain into the nozzle where it is then forced through a mesh along with the foam solution. While passing through the mesh the air is agitated into the foam solution which results in the production of the expanded foam.

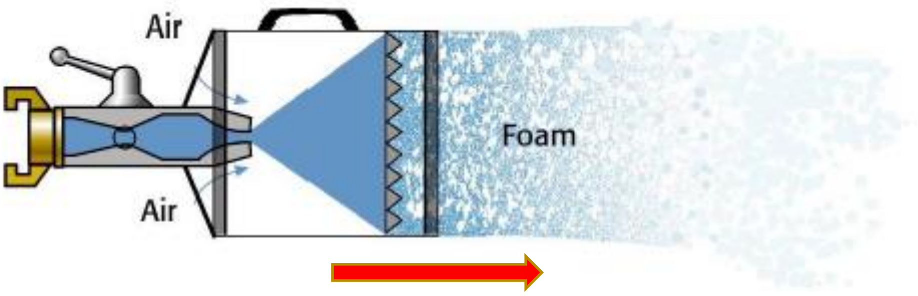

Figure 2.10: Principle of medium expansion foam [29].

The type of foam produced is dependent on the following:

- Amount of foaming agent added to the water
- Design of the nozzle (i.e. amount of air allowed to enter into nozzle)
- Size of mesh

The expansion ratios for various categories of expanded foams are shown in Figure 2.11. Low expansion foams are typically characterized as foams with an expansion ratio of 1:1 – 20:1 (i.e. one volumetric unit of foam solution will produce up to 20 volumetric units of foam). Low expansion foams are classified as “wet” foams and typically constitute of a Class A foam percentage of 0.5 %. Medium expansion foams on the other hand are categorized as expansion foams with an expansion ratio ranging from 21:1 – 200:1 and are generally applied when attempting to combat wildland fires and vehicle fires. For medium expansion foams the foam percentage is increased to 0.5 – 0.7 %, thereby allowing for the formation of larger air bubbles. Lastly, high expansion foams form the “driest” of all expansion foams due to the vast amount of air allowed to enter the foam solution through the nozzle head. High expansion foams are typically applied in large structural fires and are characterized by an expansion ratio ranging from 201:1 up to 1000:1 and contain 0.7 – 1.0 % foam concentrate [30].

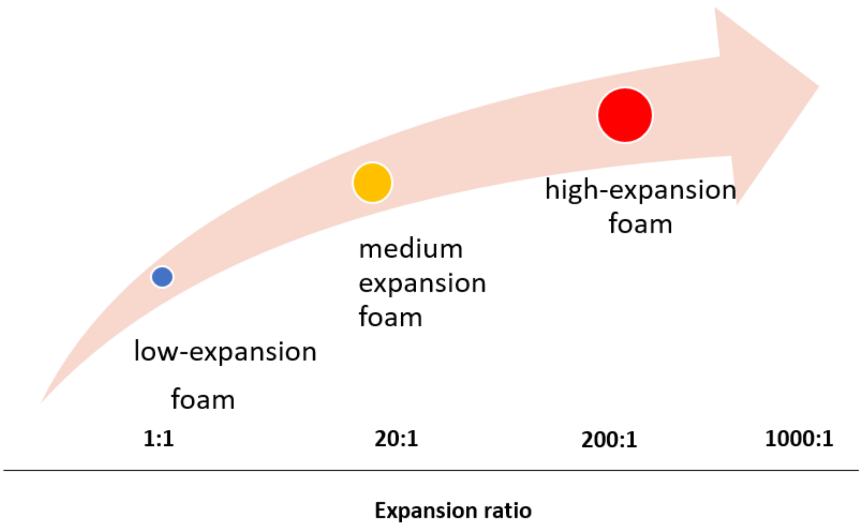

Figure 2.11: Classification of expanded foams according to their expansion ratios.

In the event of a fuel spill, the application of expansion foam will lower the temperature within a compartment, since the foam will absorb a portion of the heat being given off by the fire. Additionally, the formation of the foam blanket over the fuel load will also provide a smothering effect which prevents the combustible gases from mixing with the air. The heat from the fire will gradually break down the bubbles within the expanded foam, which could potentially lead to the destruction of the foam blanket. It is therefore pivotal to ensure that the expansion foam is applied at a rate which is sufficient to prevent the destruction of the foam blanket [31]. The rate of application, also known as the duration, is dependent on various factors which include:

- Environment
- Temperature of fire
- Type of fuel

The environment in which the expansion foam is applied will affect the effectiveness of the foam. For instance, a foam which is applied to a wildland fire in a windy environment will be much less effective than the case in which the same expansion foam is applied to a compartment fire with identical fuel and temperature conditions, since the wind would cause the foam blanket to break down much faster, thereby removing the protective blanket [31]. Secondly, the temperature of the fire will impact the duration of the foam barrier and consequently the rate of re-application, since hotter temperatures will result in an increased rate of degradation of the foam blanket.

A low expansion foam with limited agitation would lead to the formation of a wetter foam with a thinner foam blanket thickness in comparison to a high expansion foam. Due to the greater density and flowability of the low expansion foam, it would be less affected by wind conditions and it would spread out over the fuel more rapidly. However, the low expansion foam possesses a shorter drainage time compared to the high expansion foam and therefore the frequency of application would be greater.

2.4.1.5. Fire extinguishing ball

The fire extinguishing ball is a throwable fire extinguishing device which has been developed from technology originating from the 19th century [32]. During the late 19th century, in the event of a fire the grenade-style fire extinguishing device, which comprised of a glass bulb filled with carbon-tetrachloride, was designed to be thrown at the seat of the fire. Upon impact the glass bulb would shatter and the carbon-tetrachloride, which acted as the extinguishing medium, would disperse and extinguish the fire. However, it was found that carbon tetrachloride was highly toxic and could cause severe damage to vital human organs such as the lung, kidneys and liver. A schematic drawing of a modern-day fire extinguishing ball is illustrated in Figure 2.12 below.

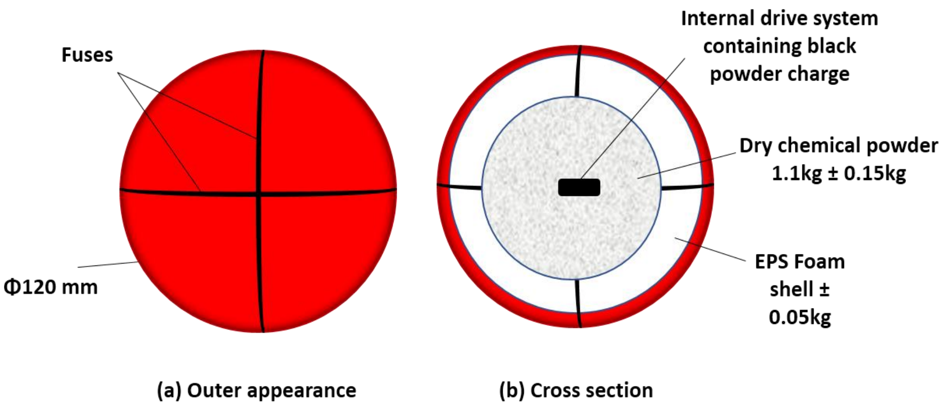

Figure 2.12: Schematic drawing of fireball extinguishing device.

Chapter 3 provides a detailed description pertaining to the activation sequence and extinguishing properties of the fire extinguishing ball, which will be utilized during the full-scale experimental testing. The activation time for the fire extinguishing ball is defined as the amount of time elapsed from the point at which the fuse has been ignited and the ABC dry chemical powder is dispersed from the expanded polystyrene foam shell. The activation time for the fireball extinguishing device typically ranges from 3 – 7 seconds, depending on the location at which the fuse was ignited.

2.4.1.6. Throwable Extinguishing Unit

The throwable fire extinguishing proprietary unit is a modern product aimed at extinguishing fires and has been developed over the past decade. In contrast to the fireball, the extinguishing agent found in the throwable extinguishing unit appears in liquid form and is made up of organic and inorganic salts of which potassium salt is the main compound. In addition to the organic and inorganic salts, a low concentration (< 1%) of fluorosurfactants is contained within the ampoule. The fluorosurfactants serve as a wetting/foaming agent, which lowers the surface tension between two fluids or between a fluid and a solid, thereby enhancing the products ability to wet and penetrate porous surfaces [29]. The effect of adding surfactants to a fluid is exemplified in Figure 2.13 from which it can be seen that the fluid containing the surfactant greatly outperforms its counterpart in terms of flowability and penetrating the surface of the burning fuel package.

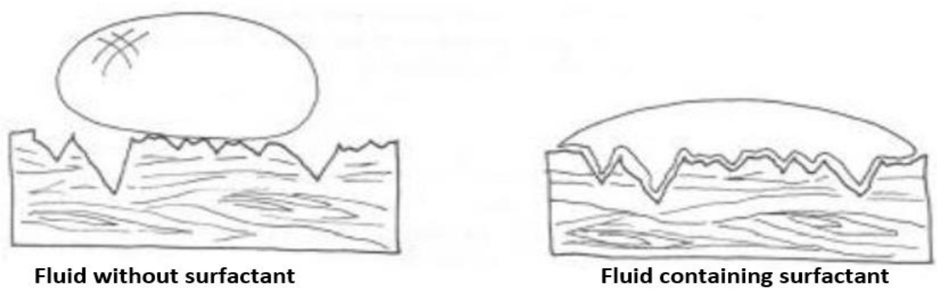

Figure 2.13: Effect of surfactants on droplet formation and spread [29].

The throwable extinguishing unit is suitable for Class A and B fires. For Class A fires the chemicals functioning as the extinguishing agent are intended to react with the fire, which in turn results in the production of extinguishing gases which consequently are supposed to knock down the fire whilst simultaneously cooling down the fuel packages, therefore preventing the fire from re-igniting. In contrast to Class A fires, the function of the extinguishing media differs for Class B fires. For Class B fires the extinguishing solution is designed to form a layer on top of the fuel source, thereby separating the fuel for the oxygen required for the combustion reaction which subsequently smothers the fire.

2.4.1.7. Inert gases

Inert gases are non-combustible gases, which are utilized during firefighting operations to extinguish fires by lowering the oxygen concentration within a closed system below the limiting oxygen concentration, which is required for the combustion reaction to be sustained. Nitrogen and Argon are the most commonly used inert gases for firefighting purposes. In the event of a fire the inert gases are released either by manual, automatic or manual pneumatic activation. Within a closed system such as an enclosure most fires are extinguished within 60 seconds after activation [33]. The oxygen concentration within the enclosure is reduced to < 15% thereby preventing the combustion reaction from occurring.

Inert gases are considered “clean agents”, since they are naturally occurring and do not have an adverse effect on the environment [33]. Furthermore, the oxygen concentration within the enclosure following the intervention of the inert gases is low enough to ensure that the combustion reaction cannot occur but remains high enough to support human life. However, inerting suppression systems require the installation of one or more cylinders containing the inert gas, as well as specialized equipment, a pipe networking system and series of nozzles. This makes inert gases unsuitable for informal settlements, which lack the necessary infrastructure required for the installation of such systems and will therefore not be considered in sections to follow.

2.4.1.8. Sprinkler Systems

It has been shown, based on the performance of automatic sprinkler systems in real-life fires, that automatic sprinkler systems are the most effective form of active fire protection technology due, to the proven ability to contain and extinguish compartment fires [1]. Sprinkler systems can be paired with fire detection sensors to automatically activate in the event of a fire and can thus extinguish or contain fires while the fire is still in its incipient stage, thereby preventing fire from spreading to adjacent compartments/structures. However, the use of sprinkler systems will be omitted from this research, since this research focusses on post-flashover fires, while automatic sprinkler systems are designed to activate before the fire reaches its flashover stage and would therefore not provide results, which can be used to draw an accurate comparison between the performance of various interventions. Furthermore, the use of automatic sprinkler systems in informal settlements is not feasible due to the absence of the required water infrastructure within these communities.

2.4.2. Passive Fire Protection

In contrast to AFP, passive fire protection (PFP) refers to fire protection products and systems which attempt to contain the fire or limit the rate of spread from the point of origin to its surrounding environment. The building layout and selection of construction materials play an integral role in PFP. Passive fire protection can be provided through fire-retardant adhesives as well as fire-resistant rated ceiling and wall boards, which compartmentalize a building into smaller sections. However, for the purpose of this research investigation the use of PFP falls beyond the scope of work and will therefore not be regarded in the sections to follow.

2.5. Benchmarking of Enclosure Fires

The suppression of enclosure fires is an essential operation aimed at alleviating the dangers associated with unexpected fires. The use of water as a suppression medium has received much attention in the past due to the low costs associated with the operation, nontoxicity and effective suppression capability. However, much attention is being directed at the development and optimization of alternative suppression products for the purpose of combating enclosure fires. To draw a comparison between the extinguishing performance it is necessary to test products or suppression strategies under similar fire conditions. Previous research has shown that one of the most prominent issues associated with developing reproducible experimental fire conditions lies with the varying material flammability characteristics [34]. The main parameter influencing the development of reproducible results is associated with the chemical heat of combustion of the fuel. It has therefore been proposed to utilize a fuel load with controlled material flammability characteristic based upon the results from the ASTM E2058 Fire Propagation Apparatus Test, which determines the effective heat of combustion of the fuel [34]. Furthermore, it has been recommended that the fuel load typically located within a compartment is to be replaced with an equivalent fuel load in the form of a timber crib, which is supported over a pan filled with heptane, thereby allowing for reproducible fire load conditions.

From previous full-scale post-flashover compartment fire experiments, it was found that the following should be considered when conducting suppression tests [35]:

- The amount of fuel located within the enclosure should be sufficient to ensure that flashover can occur before the available fuel has been consumed.
- The fire should not be so large that it consumes all the available oxygen, thereby lowering the oxygen concentration below the required concentration necessary for combustion, thus resulting in self-extinguishment.
- If the degree of suppression is insufficient, the fire should grow slowly and involve fuel not consumed prior to the initial intervention.

A number of investigations focussing on the suppression of post-flashover compartment fires have been carried out in the second half of the 20th century [36]-[39]. Table 2.3 provides a summary of details and results pertaining to the compartment and fire as documented by previous researchers, while Table 2.4 provides a summary of the suppression results for the respective experiments. All flow rates listed in Table 2.4 were sufficient to extinguish the fire. For the experiments listed below, the definition of flashover varied. A temperature of 600 – 650 °C measured within the upper hot layer was typically defined as the point at which flashover occurred. In all tests, suppression was defined as the point at which no flames were visible within the compartment.

Table 2.3: Summary of compartment and fire properties and results of previous research [36]-[39].

	Borehamwood tests (mock furniture) [36]	University of Karlsruhe tests (wood cribs) [37]	University of Karlsruhe tests (real furniture) [37]	Salzberg et al (real furniture) [38]	Fire Technology Laboratory Finland [39]
Room Dimensions: Area [m²] Height [m] Volume [m³]	18 2.8 50	12.8 2.8 36	12.8 2.8 36	13.4 2.4 32	8.6 2.4 21
Ventilation Area A√H [$m^{5/2}$]	7.13	1	1	4.0 + door	2.3
Mass of fuel [kg]	360	380	380	300	20 + walls and ceiling
Surface area of fuel [m²]	67.3	112	40	N/A	43
Mass loss rate [kg/min] 6.5A√H	46.3	6.5	6.5	26.0	15.0
Actual mass loss rate after flashover [kg/min]	72	10.4	11.3	N/A	15.9
Time to flashover	5 - 10 min	28 - 35 min	5 - 25 min	N/A	4 - 5 min

Table 2.4: Summary of suppression results of previous research [36]-[39].

	Borehamwood tests (mock furniture) [36]	University of Karlsruhe tests (wood cribs) [37]	University of Karlsruhe tests (real furniture) [37]		Salzberg et al (real furniture) [38]	Fire Technology Laboratory Finland [39].
Flow rate [lpm]	22.7-113.7	20-100	100	15-25	25-112	46
No. Tests	40	3	2	1	17	1
Pressure [bar]	5.6	5	5	5	17	2
Time after flashover before intervention [min]	2 min	12 min	13 min	11 min	0.5 - 2 min	1 - 2 min
Water used to extinguish [l]	76.0	162.0	225.0	152.0	50-80	25-43
Water collected [l]	0	64	126	50	N/A	N/A
Water evaporated [l]	76.00	98	99	102	N/A	N/A

2.6. CFD Modelling

In recent years, the fire engineering industry has experienced a significant increase in the use of computer models for simulating the behaviour of enclosure fires. This may be attributed to various factors such as the increased complexity of building designs and layouts, improved understanding of fire dynamics and, most importantly, technological advances in computer software. There are two approaches which can be adopted when modelling enclosure fires, namely the use of probabilistic models and deterministic models. Deterministic models directly utilize the chemical and physical principles associated with fires, whereas probabilistic models rely on statistical predictions regarding the development of compartment fires. Deterministic models can be subdivided into three primary categories namely computational fluid dynamics (CFD) models, zone models and hand calculation models [3]. For the purpose of this research investigation the focus will be directed towards CFD models and the use of probabilistic models as well as zone models will be omitted from this research.

2.6.1. Overview of CFD modelling

CFD models are the most advanced of the three deterministic models which are used to simulate the behaviour of enclosure fires and are often referred to as "field models". CFD focuses on the simulation of fluid engineering systems using modelling and numerical methods [40]. This is achieved by obtaining a complete, time-dependant solution based on the fundamental laws of conservation. CFD modelling is based on subdividing the volume space under consideration i.e. the computational domain into a vast number of small sub-volumes (cells) and applying the fundamental laws of mass, moment and energy conservation to each of these. Figure 2.14 illustrates how the computational domain is divided up into cells to which the fundamental laws of mass, moment and energy conservation will be applied.

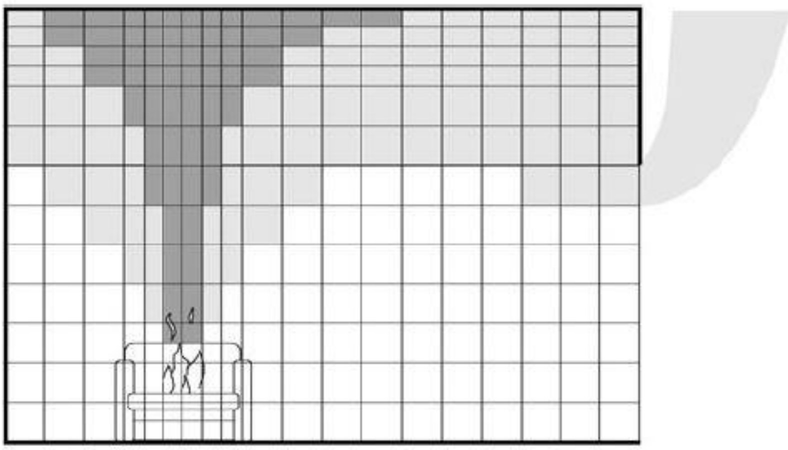

Figure 2.14: Subdivision of control volume for CFD models [3].

The Navier-Stokes equations exemplify the relationship between velocity, temperature, pressure and density of a moving fluid and form the core equations required to solve CFD problems. The Navier-Stokes equations comprise of a single time-dependent continuity equation based on the conservation of mass, three time-dependent conservation of momentum equations and a further time-dependent equation based on the conservation of energy [41]. The respective conservation equations are listed below:

Continuity Equation:

$$-\rho\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)=0 \tag{2.9}$$

Conservation of Momentum equations:

$$\rho g_x - \frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = \rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) \tag{2.10}$$

$$\rho g_y - \frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) = \rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) \tag{2.11}$$

$$\rho g_z - \frac{\partial P}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) = \rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) \tag{2.12}$$

Conservation of Energy:

$$\begin{aligned}\frac{\partial(E_t)}{\partial t} + \frac{\partial(uE_t)}{\partial x} + \frac{\partial(vE_t)}{\partial y} + \frac{\partial(wE_t)}{\partial z} \\ = \frac{\partial(up)}{\partial x} + \frac{\partial(vp)}{\partial y} + \frac{\partial(wp)}{\partial z} - \frac{1}{RePr}\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right) \\ + \frac{1}{Re}\left[\frac{\partial}{\partial x}(u\tau_{xx} + v\tau_{xy} + w\tau_{xz}) + \frac{\partial}{\partial y}(u\tau_{xy} + v\tau_{yy} + w\tau_{yz}) \right. \\ \left. + \frac{\partial}{\partial x}(u\tau_{xz} + v\tau_{yz} + w\tau_{zz})\right]\end{aligned} \tag{2.13}$$

Where:

(x, y, z)	- global coordinates	
(u, v, w)	- directional components of velocity of the fluid	
g	- gravity	[m/s²]
P	- pressure	[Pa]
μ	- viscosity	[Pa·s]
ρ	- density	[kg/m³]
t	- time	[s]
Re	- Reynolds Number	[-]
Pr	- Prandtl Number	[-]
τ	- Shear Stress	[Pa]
E	- Energy	[J]

There are numerous CFD software programmes commercially available which essentially consist of code containing a pre-processor, solver and post-processor. During the pre-processing phase the geometry of the space is defined, a grid for the control volume is generated, boundary conditions are allocated, and material attributes are assigned. During the solving process, the unknown parameters for the subsequent time step are approximated by solving the Navier-Stokes equations. Lastly, during the post-processing stage the input and output data is displayed in visual terms using grid displays, vector plots, contour plots etc. [3]. A simplified procedure for CFD modelling is illustrated in Figure 2.15.

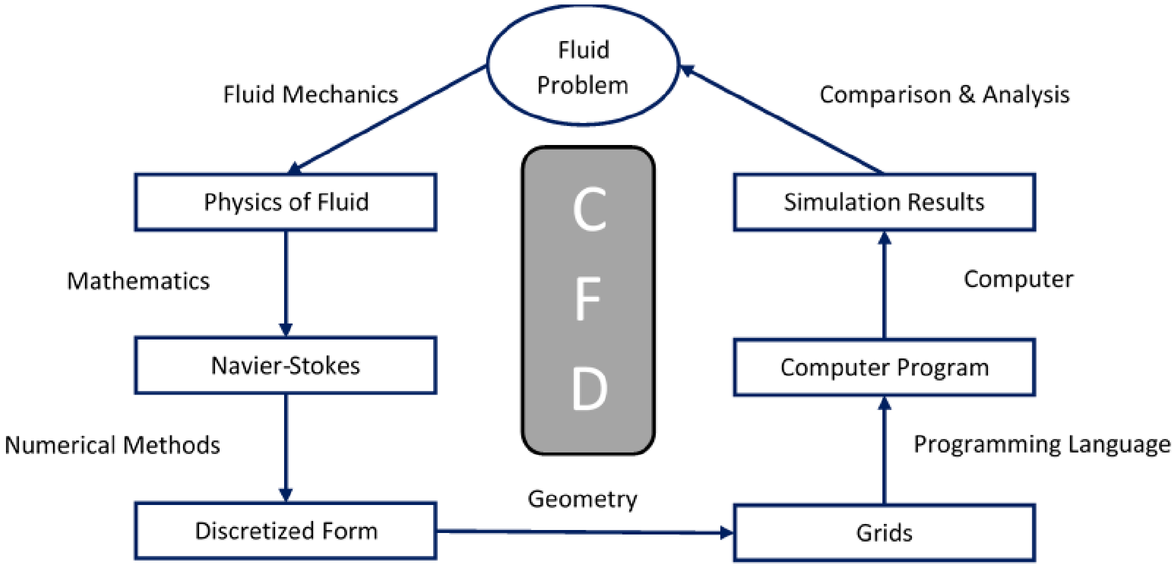

Figure 2.15: CFD modelling procedure [40].

2.6.2. Suppression modelling

The suppression modelling conducted throughout this research investigation will be performed using Fire Dynamic Simulator, a CFD modelling software specialising in fire-driven fluid flow [35]. The suppression modelling performed will be strictly limited to suppression by water and will not consider other extinguishing media. This section seeks to provide a brief background as to how the FDS software package approaches modelling suppression by water. Previous work has focused on validating the use of FDS for informal settlement fires [17][19].

The modelling of fire suppression using water as an extinguishing medium consists of three primary components, namely [42]:

- Transportation of the water particles through the computational domain.
- Tracking of the water particles along a surface.
- Anticipating the response of the HRR based on the reduction of the burning rate.

The reduction of the burning rate is the most important factor for this investigation and will therefore be discussed in further detail. The information in the following section has been sourced from [42] unless stated otherwise.

As water interacts with a burning surface it provides a cooling effect to the surface, consequently reducing the rate of pyrolysis and therefore the burning rate of the fuel. Developing an accurate pyrolysis model is challenging due to the inherent complexities associated with the pyrolytic decomposition of the fuel, which in itself consists of a series of complex sub-reactions. It is therefore often preferred to use a simplified pyrolysis model by applying a prescribed Heat Release Rate per Unit Area (HRRPUA) to a surface, which essentially acts as a burner, releasing gas at a specified rate. As a result of the simplified pyrolysis model, a parameter needs to be assigned to the model which governs the suppression response once water is introduced to the model. This is achieved by assigning a parameter which is responsible for the exponential decay of the pyrolysis rate following the application of water. The so-called "extinguishing coefficient" governs the burning rate reduction as shown in Equation 2.14 [42]:

$$\dot{m}_f{}^{"}(t) = \dot{m}_{f,0}{}^{"}(t)e^{-\int k(t)dt} \tag{2.14}$$

Where $\dot{m}_{f,0}{}^{"}$ $[\frac{kg}{sm^2}]$ is the original user-defined mass loss rate per unit area prior to the introduction of water into the computational domain, while $\dot{m}_f{}^{"}$ is the reduced mass loss rate per unit area at a given time following the initiation of the suppression phase. The parameter k(t) is a function of the extinguishing coefficient and the water mass per area, $m_w{}^{"}$ $[\frac{kg}{m^2}]$, which dictates the reduction of the mass loss rate [42]:

$$k(t) = E_{COEFFICIENT}\, m_w{}^{"}(t)\ \left[\frac{1}{s}\right] \tag{2.15}$$

The use of the extinguishing coefficient for fire suppression modelling has been investigated by other authors [43][44]. The latter focussed on obtaining an appropriate value for the extinguishing coefficient based on full-scale experimental work in which a 0.3 m x 0.3 m pan filled with n-Heptane was placed in the centre of a 5.4 m x 3.1 m x 2.4 m compartment with a 1.1 m x 1.9 m high door situated within one of the long sides of the compartment. The water mist nozzle was set to activate 10 seconds after the ignition of the pan fire. Figure 2.16 depicts the influence of the extinguishing coefficient on the suppression duration. The author found that an extinguishing coefficient of 16.4 results in an extinguishing time of 2.5 seconds, which corresponds with the experimental results.

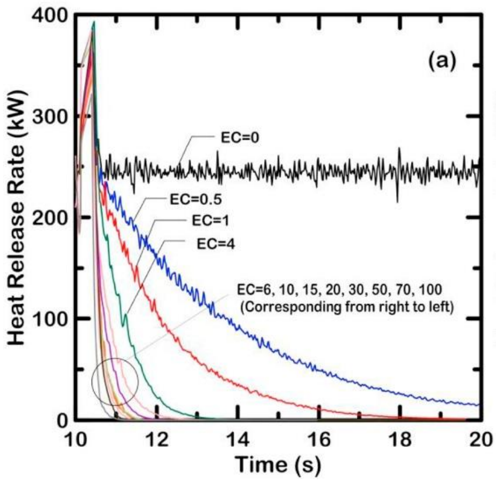

Figure 2.16: Investigation of the effect of the extinguishing coefficient on the suppression time [44].

However, both [43][44] acknowledge that the use of the extinguishing coefficient is currently limited, due to many factors influencing the determination of the extinguishing coefficient, which include the effect of the compartment dimensions (height of the ceiling results in a delay between the time of intervention and measured temperature reduction), water spray properties (flow rate, spray angle, droplet size etc.). Due to the many variables associated with the determination of the extinguishing coefficient it is currently suitable to use the extinguishing coefficient for modelling purposes if experimental data is available for the calibration thereof and care should be taken when using the extinguishing coefficient for predictive simulations.

2.7. Summary

From this chapter it can be seen that informal settlement fires are an emerging field of study with high levels of uncertainties associated with parameters pertaining to the fire development and suppression response. This chapter has provided an in-depth review of various aspects surrounding informal settlement fires and active fire protection. The key principles of fire safety, fire dynamics of enclosure fires, fire protection strategies etc. were discussed. The basics of fire development within ISDs are addressed to gain an understanding of how various parameters influence fire development. An overview of active fire protection is presented along with various existing active fire protection systems, which are being advertised to municipalities for the purpose of suppressing post-flashover informal settlement fires.

The aspects addressed in this chapter serve as a foundation for the full-scale experiments conducted in Chapter 3, which seeks to develop a novel testing methodology for benchmarking various existing fire protection strategies. Lastly, the concepts for the modelling fire suppression by means of water in CFD software are introduced, which will be used for the development of numerical models in Chapter 4.

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Chapter 3: Development of a full-scale testing methodology for benchmarking fire suppression systems for use in informal settlement dwellings

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Declaration by the candidate:

The nature and scope of the candidate's contribution were as follows:

Nature of contribution	Extent of contribution (%)
i. Planning of experimental setup and execution ii. Ordering and preparation of instrumentation iii. Assembly of experimental setup iv. Execution of full-scale tests v. Preparation of manuscript vi. Data Analysis	85%

The nature and scope of the co-author contribution were as follows:

Nature of contribution	Extent of contribution (%)
i. Supervision and guidance of the work ii. Assisted with the execution of the full-scale tests iii. Revision of the manuscript	15%

Signature of candidate: Stefan Löffel
Date: 27 September 2019

The undersigned hereby confirm that:

1. The declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-author to Chapter 3.
2. No other authors contributed to Chapter 3 besides those specified above, and
3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 3 of the thesis

Signature	Institutional affiliation	Date
Stefan Löffel	Stellenbosch University	27 September 2019
	Stellenbosch University	27 September 2019

This chapter is an exact copy of the journal paper referred to above

Contribution of chapter to thesis

Chapter 3 predominantly focusses on the development and execution of a novel full-scale experimental testing methodology, which can be adopted for benchmarking the suppression performance of various existing active fire protection strategies for the use in post-flashover informal settlement fires. The proposed testing methodology seeks to provide municipalities with a decision-making tool when considering a variety of active fire protection strategies. A series of nine full-scale fire experiments are conducted on a single representative steel cladded informal settlement dwelling. In this chapter the suppression performance of various existing active fire protection strategies is evaluated based on the temperatures measured at ceiling level within the dwelling, as well as on visual observations. The data obtained during the execution of the full-scale experiments serves as a foundation for the development of numerical models addressed in Chapter 4.

3.1. Abstract

Informal settlements (also referred to as slums, shantytowns or squatter camps) are expanding at a rapid rate with more than a billion people currently residing in informal settlements worldwide. The dwellings within these communities are often constructed from readily available materials, making them susceptible to large conflagrations. Within the South African context, there is significant political pressure on governmental agencies to develop and implement interventions to suppress informal settlement fires. However, many proposed solutions lack a sound scientific validation. This paper proposes a full-scale fire testing methodology for benchmarking various suppression systems against each other, using a representative informal settlement dwelling. The aim of the methodology is to assist decision-making when assessing which interventions will be most suitable in post-flashover informal settlement fires. The testing methodology can be carried out without the need for sophisticated equipment, making it readily available to fire brigades and municipalities. In this work a total of nine experiments were conducted which included: brigade-based, community based as well as non-water-based interventions. It was observed that the water-based interventions typically outperformed the remaining interventions, since they suppressed the fire while simultaneously providing a cooling effect, thereby lowering the temperature within the dwelling below the auto-ignition temperature of the fuel, thus preventing re-ignition from occurring. A model is proposed for comparing the efficacy of products based upon the analytical hierarchy process. The results from these types of tests could be adopted as a decision-making tool by the respective authorities thereby potentially preventing costly investments in products that are not suitable for the cause.

KEYWORDS: Informal settlement fires, active fire protection, fire dynamics, full-scale experiments

3.2. Introduction

Informal settlements (IS) are residential areas which form an iconic part of the South African landscape and can formally be defined as an assortment of informal dwellings which have been constructed illegally on land which has not been lawfully surveyed or proclaimed for residential purposes by the appropriate authorities [1]. Within the South African context, informal settlements are alternatively referred to as *slums, shantytowns,* and even *squatter camps* [2]. The informal dwellings within these communities, also known as *shacks,* can be classified as temporary makeshift structures, which are constructed from readily available materials such as wood, corrugated roof sheeting and various plastics, thereby making them inherently susceptible to fires. An example of such structures is shown in Figure 3.1. In addition to the makeshift nature of the structures, the following characteristics are often associated with informal settlements: (a) poorly constructed dwellings (b) inadequate access to basic services such as electricity and running water (c) lack of security of tenure (d) limited access to employment opportunities, and (e) high dwelling densities [3].

Figure 3.1: Dwellings within a typical South African informal settlement.

Fire incidence data gathered by the Fire Protection Association of South Africa (FPASA) has revealed an alarming increase in the number of reported informal settlement fires across South Africa between 2003 and 2016[4]. Figure 3.2 depicts the number of reported fires within informal settlements during this period along with estimates obtained from the National Census regarding the number of people estimated to be living in informal settlements across South Africa [1][4]. From Figure 3.2 it can be noted that South Africa has seen an increase of approximately 65% in the number of reported informal settlement fires within a span of 13 years. Furthermore, one must take into accout that these statistics simply account for the number of reported fires and do not consider the fires that were not reported to the local authorities.

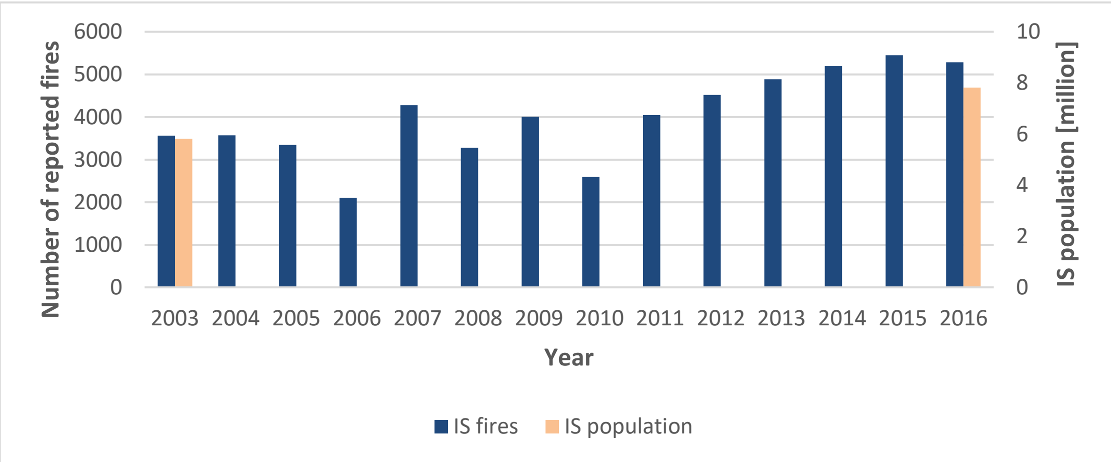

Figure 3.2: Reported number of informal settlement fires in South Africa and number of informal settlement dwellers [1][4].

The frequency and severity of these informal settlement fires not only places an enormous financial burden on the victims of the affected dwellings but also on the government and local authorities. Between 2003 and 2016, it has been estimated that the direct average annual costs associated with fighting informal settlement fires in South Africa is approximately US$7.02 million per year [4]. Currently, there is limited research available on the use of active fire protection in the event of informal settlement fires. Several concerted efforts have been made to combat informal settlement fires by means of various proposed interventions, which include sprinkler systems, smoke alarms and throwable extinguishing devices etc. [5]. However, these proposed solutions often lack a sound scientific validation and do not quantify the performance and practicality thereof. Furthermore, the proposed interventions often do not account for particularities such as the socio-economic issues within these poverty-stricken communities. The success of proposed interventions is partially governed by social factors, which include theft, vandalism, capital and maintenance costs as well as community acceptance i.e. cultural preferences [6].

The primary goal of this research paper is to develop a full-scale testing methodology for benchmarking the performance of various existing active fire suppression systems for post-flashover (i.e. fully-developed) informal settlement fires, thereby providing a preliminary indication on the effectiveness of each suppression system. The outcomes of the full-scale testing could potentially assist in the decision-making process by governments and local authorities when considering which suppression system to implement, thereby avoiding costly investments in systems that are unsuitable for post-flashover informal settlement fires. Although this paper contains much detail regarding the fundamentals of fire dynamics, this has been included for those outside of the fire science field such that the work can be appreciated and applied by a wider audience. The scope of this research paper is explicitly limited to the use of active fire suppression systems. Passive fire suppression systems (e.g. construction products, firewalls, etc.) fall beyond the scope of this investigation and will not be addressed in detail. The suppression systems which are utilized throughout testing are only utilised once post-flashover conditions have been achieved, since it is relatively simple to suppress a fire when it is in its incipient phase, and thus would not provide an accurate indication of the suppression abilities of the various interventions. Since informal settlements inherently do not adhere to codes of practice regarding construction products, it is difficult to produce a code for suppression products. Hence, the emphasis in this work is on benchmarking products, rather than having a pass/fail code requirement.

3.3. Fire Safety and Behaviour in Informal Settlements

This section aims to provide the reader with the most important information required to develop a core understanding of fire development and active fire protection for compartment fires. This paper does not focus on analyses regarding fire dynamics, which has been addressed by authors in other literature [7] and will also be the focus of future work conducted by the research team.

3.3.1. Stages of Fire Development

The development of a fire within an informal settlement dwelling closely resembles that of an enclosure fire and can therefore be categorized into several characteristic stages, namely: (a) ignition (b) growth (c) flashover (d) fully developed fire and (e) decay, which are depicted in Figure 3.3 [8]. During the experimental work it was observed that in some instances there was a sudden dip in temperature during the flashover stage, which represents the transition period during which the cardboard lining burns out and the timber fuel cribs within the compartment ignite, and this is also shown in Figure 3.3. In traditional enclosure fires this typically does not exist.

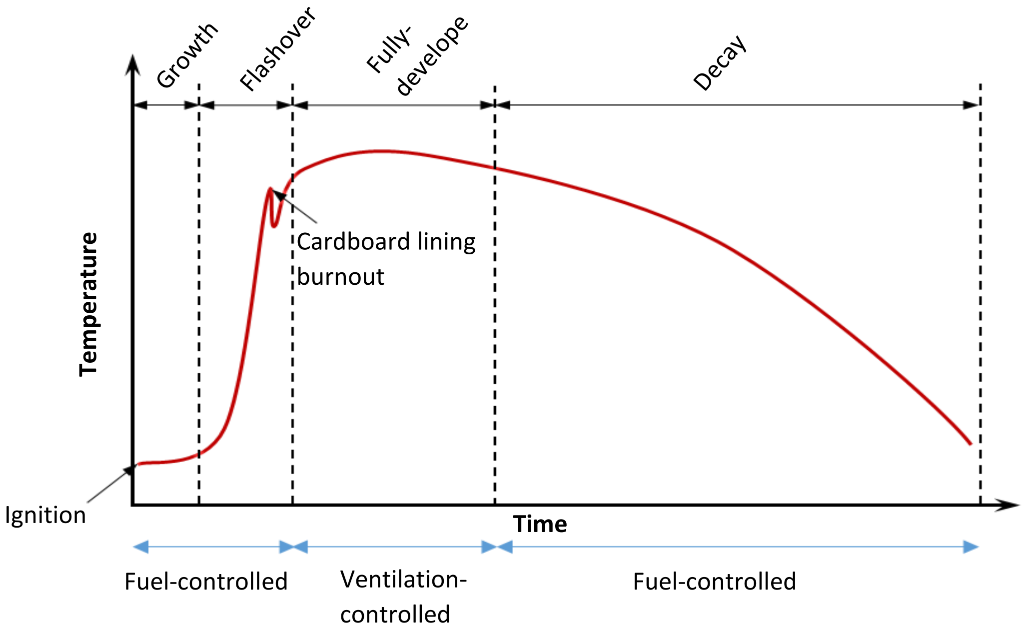

Figure 3.3: Stages of fire development as applied to informal settlement dwellings

Ignition symbolizes the beginning of the exothermic chemical reaction known as combustion. In informal settlement dwellings this can be caused by open flames utilised for cooking and heating purposes, faulty electrical wiring, candles or arson [4]. At this stage, the compartment geometry has a negligible influence on the development of the fire and therefore the fire is fuel-controlled i.e. the growth of the fire is limited by the type, amount and geometry of combustible material within the dwelling [8].

The growth phase of an enclosure fire ensues after successful ignition and is signified by an increase in the heat release rate (HRR), which refers to the amount of energy released from the combustible material over a certain time. The hot gases released as products from the combustion reaction rise to the ceiling of the enclosure due to buoyancy forces, where they accumulate, which results in the formation of a hot layer. The accumulation of hot gases and the formation of a hot layer leads to the transfer of heat to other nearby combustible materials within the dwelling, predominantly by means of radiative heat transfer, which can in turn cause them to ignite. As the fire develops, it releases additional hot combustion gases which rise and accumulate at ceiling level, thereby causing the hot layer to descend further down into the compartment and radiate additional heat onto the surfaces of the directly exposed combustible materials. This can result in a rapid transition from localized burning within the enclosure to full room involvement of all combustible material which is referred to as *flashover* [9]. For flashover to occur it has been studied that the temperature within the compartment should typically reach 500 – 600 ^{o}C, or the radiation experienced at ground level should be in the vicinity of 15 – 20 kW/m^2 [8]. Once flashover has occurred the fire is said to be fully developed and is often referred to as a *fully-developed fire* or *post-flashover fire*. During this phase the fire is predominantly ventilation-controlled, since the combustion reaction is limited by the amount of oxygen entering through the compartment openings.

3.3.2. Fire Safety

The primary objective of fire safety is to reduce the probability and severity of injury, damage and death during the event of a fire, to a level which is deemed acceptable [10]. During the incipient phase of a compartment fire, the main objective of fire safety is to protect the lives of occupants within the structure and evacuate them to a point of safety. However, during the fully-developed phase of a compartment fire, the main objectives are to ensure the safety of firefighters, prevent the spread of the fire and maintain the structural integrity of the structure itself as well as the surrounding structures [8]. The suppression of fires can be achieved by targeting the various aspects which allow for the combustion process to be sustained, which include (a) removal of heat thereby lowering the temperature required for the combustion reaction (b) smothering i.e. separation of the combustible material from the oxygen required for the combustion process (c) starvation i.e. removal or separation of the combustible material from the burning environment (d) inhibition – disruption of the chemical chain reaction [11].

Fire protection can be influenced by the selection of construction materials, structural layout, insulation materials and suppression products. Fire protection methodologies can be categorized into two distinct categories, namely active fire protection (AFP) and passive fire protection. AFP refers to fire protection products and systems which are designed to intervene in the event of a fire either by manual or automatic activation, where the automatic activation typically relies on a network of sensors [12]. The focus of AFP is to suppress fires and is predominantly provided in the form of fire detectors and alarms, fire extinguishers, sprinkler systems and smoke management systems. In contrast to AFP, passive fire protection attempts to contain fires or limit the rate of spread using compartmentation, fire-resistance rated walls and ceilings, as well as fire-resistant adhesives.

3.3.3. Classification of Fires

Depending on the properties of fuel contained within an enclosure it is possible for different types of fires to develop, each having a unique set of characteristics influencing their development and ease of suppression. Adhering to the classification system utilized by SANS 1107:2015, fires can be classified according to Table 3.1.

Table 3.1: Classification of fires according to SANS 1107:2015 [13].

Classification	**Description**
Class A	Fires which comprise of organic combustible solids such as wood, paper, rubber, fabric and plastics which do not melt
Class B	Fires which comprise of combustible liquids or liquefiable solids such as petroleum, oil and paints (excluding cooking oils and fats)
Class C	Fires which comprise of combustible gases such as propane, natural gases and hydrogen
Class D	Fires which comprise of combustible metals such as magnesium, lithium etc.
Class F	Fires which involve cooking oils and fats

The type of fuel contained within an enclosure to a large extent predetermines the development of the fire and influences the type of fire protection required to extinguish the fire. In informal settlement dwellings the combustible materials within the enclosure mostly result in the development of Class A fires, although during cooking Class F fires could occur.

3.4. Experimental Setup

Due to the limited research conducted on the use of AFP products in the event of informal settlement fires it was required to prepare and execute a series of full-scale tests under uniform conditions. Based on the results from the experimental testing, the data can then be analysed to establish a direct comparison between the performances of the various interventions. This work follows on previous full-scale informal settlement dwelling testing, which provides the basis for the methodologies employed in this work [7][14].

3.4.1. Representative Structure and Instrumentation Layout

For this investigation the representative structure consisted of a steel frame built from 32 x 3.0 mm square hollow steel tubing, thus providing a frame which would not collapse during testing. The representative structure was cladded with 0.58 mm galvanized IBR steel sheeting and is depicted in Figure 3.4.

Figure 3.4: Representative Informal Settlement Dwelling.

The dimensions of the structure utilised throughout this investigation are based on the dimensions of the ISO 9705 room [15] and are depicted in Figure 3.5. The ISO 9705 room dimensions were used due to its wide utilisation in other research investigations and therefore the experiments can be easily reproduced. The interior dimensions of the dwelling are 2.4 x 3.6 x 2.4 m with a door of 0.8 x 2.0 m situated in centre of the front panel. The only deviation from the ISO 9705 room is the addition of a 0.80 x 0.80 m window located in the centre of the side panel as indicated in Figure 3.5. This deviation from the standardized room was made, since informal settlement dwellings often have one window situated within the confines of their boundary walls.

The structure was equipped with 35 Type K 2.0 mm diameter thermocouples and 21 Thin Skin Calorimeters (TSCs), where the TSCs were constructed in accordance to [16]. The thermocouples and TSCs utilized throughout the full-scale tests were secured to equipment trees and connected to data loggers. The height distribution of the thermocouples and TSCs placed across the height of the door and window is indicated in Figure 3.5, where the number in the brackets indicates the number of instruments located within a given equipment tree. The thermocouples distributed along the length of the roof (i.e. T9, T10 & T11) were placed at 150 mm from ceiling level while the thermocouples along the back panel were placed at 150 mm, 640 mm, 1140 mm and 1640 mm from ceiling level, respectively. It should be noted that the representative test structure was extensively equipped with instrumentation to document the time-temperature response during testing. However, in the future if the test was to be done by municipalities the instrumentation is not essential, since the effectiveness of the interventions can be evaluated explicitly based on visual observations.

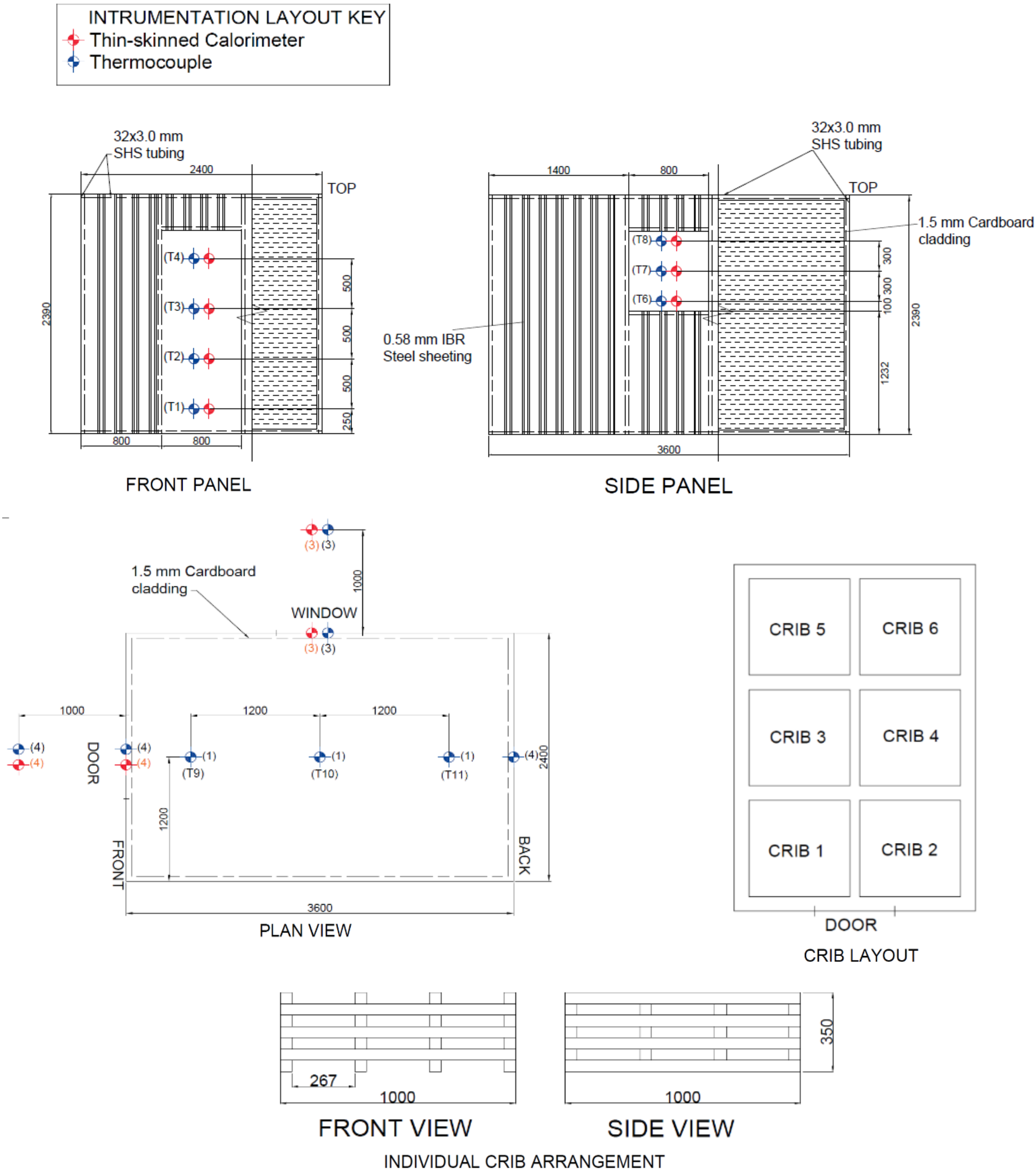

Figure 3.5: Experimental layout and instrumentation. All dimensions in mm.

3.4.2. Representative Fuel Load

The fuel load density (measured in MJ/m²) refers to the fire load per unit floor area, i.e. the amount of energy that can be released per unit floor area during the complete combustion of all combustible material. The fire load density, to a large extent, determines the growth and intensity of a fire. It should be noted that the fuel load within informal settlement dwellings differs significantly from one dwelling to another due to the selection of construction materials and the varying contents within the dwellings itself, thereby making it difficult to define a typical fuel load density for informal settlement dwellings. A fire load density of 780 MJ/m² is prescribed for formal residential structures according to EN-1991-1-2 [17]. However, based on an independent study performed by Stellenbosch University, which included fire load surveys in informal settlement dwellings, it was found that the average fire load density was in the vicinity of 414 MJ/m² for informal settlement dwellings [18], although further research is required. It was decided to use 50 x 50 mm non-structural pine with a calorific value of 16.1 MJ/kg (as determined from a bomb calorimeter test), fuel load of 25 kg/m², and density of approximately 530 kg/m³. The timber crib arrangement adopted for this investigation is shown in Figure 3.5. In addition to the fuel load provided by the timber, the interior walls as well as the floor of the dwelling were lined with cardboard, as depicted in Figure 3.6, which was performed in order to replicate the nature of informal dwellings which often utilise cardboard as an insulation material, since it provides some relief against the hot summer days and cold winter nights. Timber products and materials such as plywood boards can alternatively also be a used to line homes. Furthermore, the cardboard lining also acts as an accelerant, since it enhances the rate of flame spread within the dwelling during testing [19]. The cardboard used for the thermal insulation is approximately 1.5 mm thick and has a calorific value and density of 16.9 MJ/kg and 180kg/m³, respectively. As a result of the cardboard insulation the combined fire load density of the dwelling was approximately 440 MJ/m².

For all tests, hessian material was rolled into a bundle and doused with paraffin before being placed into a steel tray (250 mm in diameter) which was placed in the far-left corner of "Crib 2". The inclusion of paraffin doused hessian bundle was based on discussions from previous tests, since the paraffin would promote initial fire growth and enhance the probability of successful ignition [20].

Figure 3.6: Cardboard cladding and timber fuel.

3.5. Full-scale experimental testing

In this section, the general experimental procedure for the various active fire suppression tests is outlined in more detail and the most important observations of the respective tests are summarised, thereby forming the basis for a comparison of the performance thereof. The full-scale experimental testing was conducted at the Epping Fire and Rescue Training Academy in Cape Town, South Africa. For the purpose of this investigation it is of interest to evaluate and compare the performance of various active fire suppression products and techniques for fully-developed informal settlement fires and therefore it was crucial to only intervene once flashover conditions were achieved. The hessian bundle contained within "Crib 2" was ignited by means of an external piloted flame, which symbolized the beginning of the test. Once successful ignition was achieved, the fire was allowed to develop until a "fully-developed fire" was attained. In order to achieve the most uniform conditions across all tests it was decided to define the instance at which the fire was "fully-developed" as the point at which a roof temperature of 850^{0}C was recorded at one of the three roof thermocouples within the dwelling. After the fire had reached the fully-developed stage the firefighters would prepare to intervene within 60 seconds and attempt to extinguish the fire. The temperature response as well as the amount of product used during the intervention phase was recorded and evaluated.

One of the most prominent issues regarding the selection of active fire suppression products for informal settlement fires, is that there is an extensive variety of products which are being marketed as suitable for the purpose. These products include brigade-based, community-based as well as non-water-based interventions. For the purpose of this research paper a variety of active fire suppression products were selected as examples of what can be used and how they compare to one another. The following nine tests were conducted:

1. *Benchmark test (no intervention)*
2. *Brigade-based interventions*
   i. Water jet
   ii. Nozzle Aspirated Foam Systems (NAFS)
   iii. Compressed Air Foam Systems (CAFS)
3. *Community-based interventions*
   i. Bucket Brigade I
   ii. Bucket Brigade II
4. *Non-water-based interventions*
   i. Dry chemical powder fire extinguisher
   ii. Throwable extinguishing unit
   iii. Fire ball dry chemical powder unit

3.5.1. Benchmark Test

The benchmark test did not utilize any intervention techniques, since the sole purpose of the test was to establish the nature of the development of the fire and to obtain a data set against which the other tests can be compared. At approximately 1.2 minutes after ignition of the hessian bundle, the flames impinged onto the cardboard lining at the window opening which prompted flashover to occur within the following 50 seconds, which is illustrated in Figure 3.7.

Figure 3.7: Flashover in the benchmark test showing flames emerging from the door.

The fire successfully achieved its fully-developed stage at approximately 4.1 minutes after ignition. Thereafter, the fire was allowed to transition into its decay phase during which the fire became fuel-controlled instead of ventilation-controlled, due to the reduction of combustible fuel contained within the dwelling. At 20.1 minutes after ignition it was decided to terminate the test and extinguish the fire. The time-temperature relationship of the average roof temperature within the dwelling is depicted in Figure 3.8, where the average roof temperature is calculated based on the temperatures recorded from T9, T10 and T11.

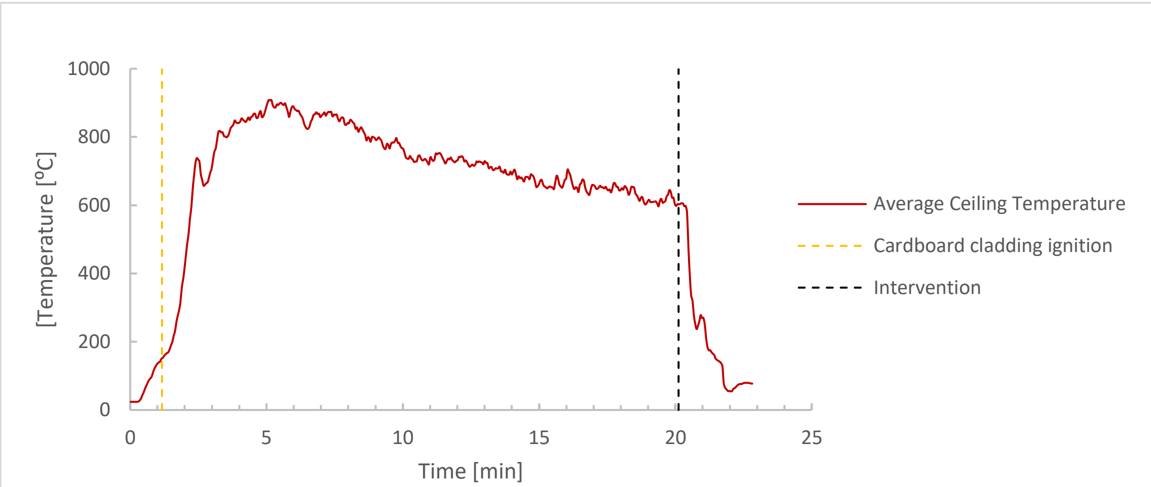

Figure 3.8: Time-temperature curve - Benchmark test

From the time-temperature curve, it can be noted that the fire is fuel-controlled during the ignition and growth phase of the fire. The sudden decrease in the temperature at approximately 2.4 minutes represents the transition period during which the cardboard lining burns out and the timber fuel cribs ignite [7]. The average roof temperature stabilized, once the fire attained its fully-developed stage, thereby signifying that the fire has become ventilation-controlled and is being limited by the amount of oxygen entering through the compartment openings. At approximately 8 minutes the intensity of the fire starts to decrease, thereby indicating the beginning of the decay phase, during which the fire once again becomes fuel-controlled due to a reduction in the amount of available combustible material.

3.5.2. Brigade-based interventions

3.5.2.1. Water Jet

For this particular test the goal was to test the performance of a water stream without the addition of a foaming agent, as typically used by a fire brigade. After discussions with the local fire department it was decided to use TFT G-Force selectable flow fog branch, set to 115 litres per minute, which was connected via a 65 mm and 45 mm diameter hose to a fire hydrant with an approximate operating pressure of 4 – 5 Bar. The cardboard lining ignited approximately 4.1 minutes after ignition, which occurred due to flame impingement at the window opening. This corresponds with the sudden increase in the average ceiling temperature depicted in Figure 3.9. Thereafter, the intensity of the fire increased as it transitioned into its fully-developed stage. At 5.9 minutes after ignition the firefighter introduced the hose line and directed the water towards the timber cribs as well as at the ceiling. After approximately 10 seconds, there were only minor flames visible in the corners of the enclosure which were obscured by the timber cribs, which made it difficult to apply water to these remote areas. The hose was removed from the dwelling at 6.9 minutes after ignition, thereby signalling the end of the test.

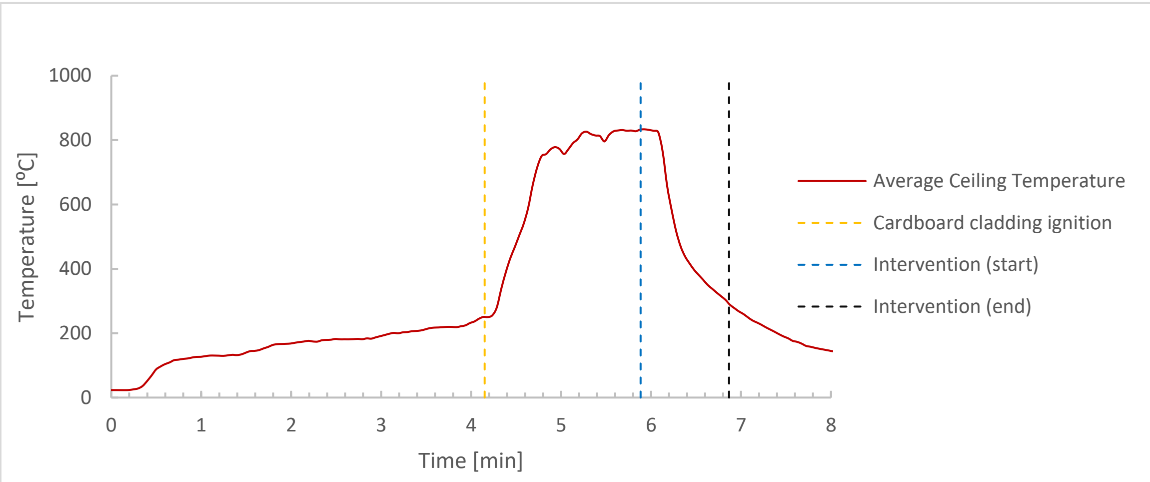

Figure 3.9: Time-temperature curve - Water Jet test

3.5.2.2. Nozzle Aspirated Foam Systems

Nozzle aspirated foam systems (NAFS) deliver a stream of water which is mixed with a foaming agent to generate a foam, which is suitable for fire-fighting operations and can be applied directly to the fire. The air required for the formation of the foam bubbles is introduced and agitated into the foam solution by means of the nozzle head where the air is able to entrain into the foam solution due to the design of the nozzle head. After consulting the local fire department, it was decided to use of a round pump proportioner to induce RLF4 foam concentrate at 1% with an approximate pumping pressure of 7 Bar. RLF4 is a general-purpose, synthetic firefighting foam concentrate designed to combat Class B fires but is also effective at extinguishing Class A fires [21]. The time-temperature curve for the NAFS test is illustrated in Figure 3.10.

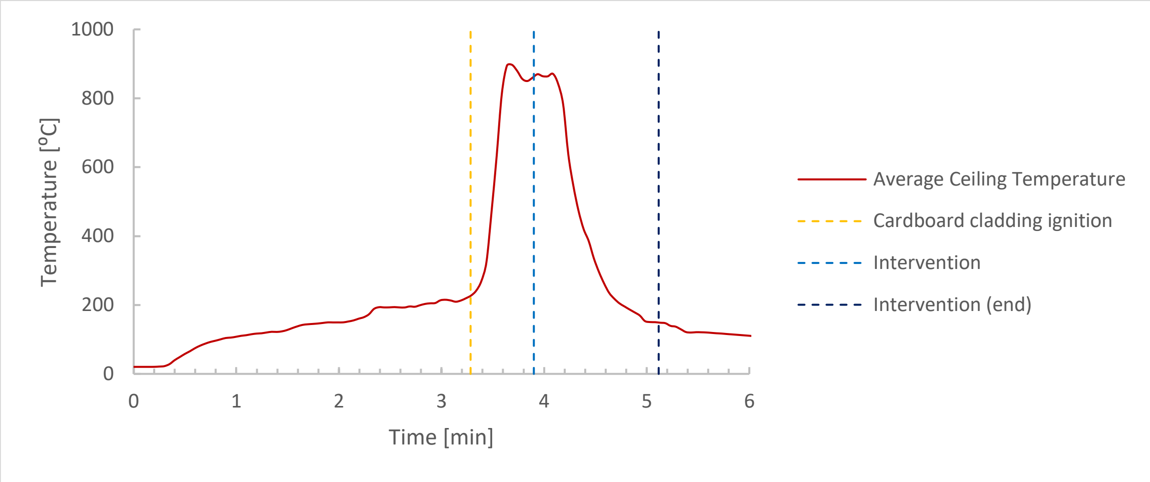

Figure 3.10: Time-temperature curve - NAFS test.

Flame impingement on the cardboard lining adjacent to the window opening occurred at approximately 3.1 minutes after ignition resulting in flashover shortly after. Once, the fire achieved its fully-developed phase the firefighters were set to intervene and suppress the fire at approximately 3.9 minutes after ignition. At 4.2 minutes after ignition, there were no visible flames within the dwelling and at 5.1 minutes, the test was concluded, and the hose was removed from the dwelling.

3.5.2.3. Compressed Air Foam Systems

Similar to NAFS, compressed air foam systems (CAFS) use a foam suitable for fire-fighting operations to suppress fires, the only difference being that the air is introduced under pressure into the water-foam solution by means of an air compressor instead of being introduced at the nozzle head. For further information about CAFS the reader is referred to [22][23]. For this test the City of Cape Town's CAFS unit was utilised which is intended for large structural fires opposed to informal settlement fires. It was opted to use 0.4% RLF4 foam concentrate under similar conditions as per the NAFS test. The time-temperature behaviour for the test is depicted in Figure 3.11.

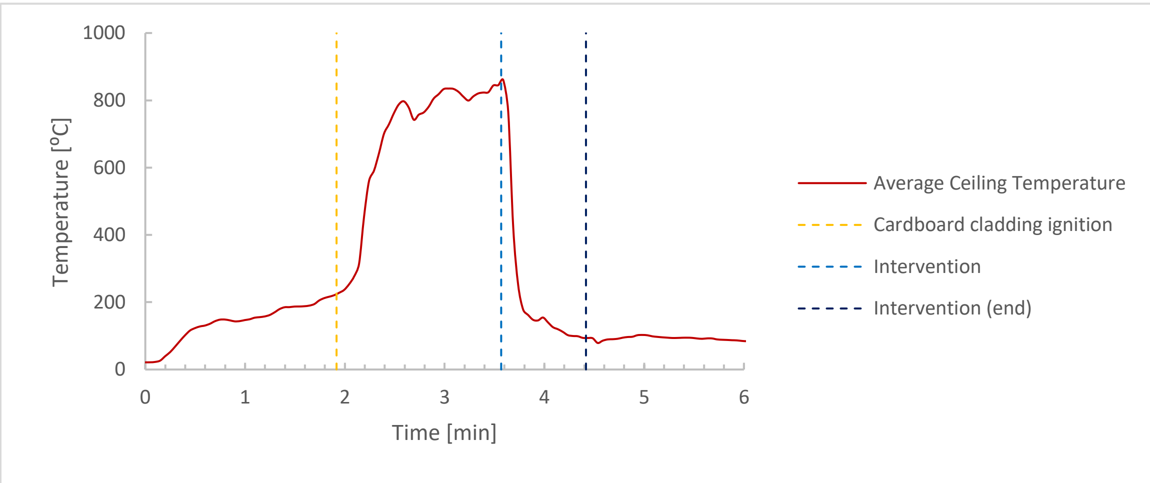

Figure 3.11: Time-temperature curve - CAFS test

At approximately 1.9 minutes after ignition the cardboard along the door opening ignited and flashover ensued approximately 24 seconds later. At 3.6 minutes after ignition the firefighters introduced the hose and set about extinguishing the fire, as illustrated in Figure 3.12. Four seconds after the introduction of the hose there were no visible flames within the enclosure. The firefighters continued to apply the CAFS to the dwelling for a total duration of 50 seconds after which the hose was removed from the dwelling and the test was concluded.

Figure 3.12: Application of CAFS

3.5.3. Community-based interventions

Bucket Brigade

A bucket brigade refers to a method of transporting objects where the object of interest is passed from one person to the next until it has reached its destination. In informal settlement communities the bucket brigade technique is often implemented by local residents when attempting to extinguish fires, since the individual dwellings do not have access to running water and therefore residents have to collect water from the nearest communal standpipe.

3.5.3.1. Continuous Application

The first of the two methods that were tested was the bucket brigade technique utilising a continuous supply of water, i.e. there is a continuous circulation of buckets filled with water being passed towards the fire. For this test a constant supply of buckets filled with 8 litres of water was circulated over a distance of approximately 20 m (distance from tap to dwelling). The time required for the application of two successive buckets varied due to the time associated with emptying, exchanging and refilling the buckets but typically ranged between 20 – 30 seconds. The corresponding time-temperature curve for the bucket brigade test with continuous application is featured in Figure 3.13.

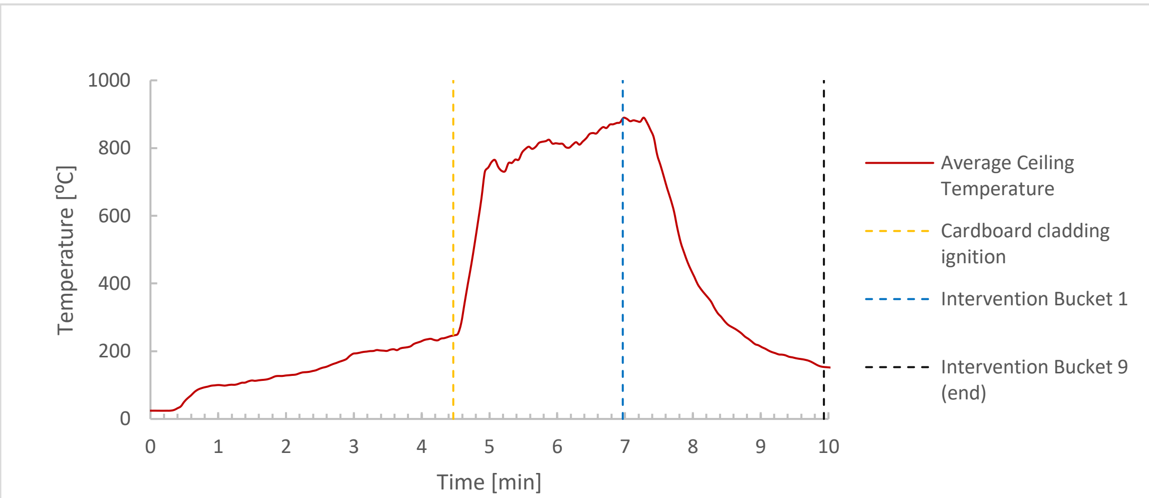

Figure 3.13: Time-temperature curve - Bucket brigade test (continuous application).

The first bucket of water was applied to the fire at 7 minutes after ignition, which did not have a significant impact on the fire as it did not result in an immediate temperature reduction within the dwelling and only lead to minor reduction in terms of the flame intensity. The second bucket of water was applied 20 seconds after the first bucket. In contrast to the initial bucket of water, the second bucket resulted in severe flame reduction within the enclosure. Although there was no drastic heat reduction within the dwelling at roof level, only minor localised flames were visible throughout the dwelling. The third and fourth buckets of water were applied at 7.7 and 8.1 minutes, respectively, after which no flames were visible. Although there were no visible flames present after the application of the fourth bucket of water, a further five buckets of water were applied to absorb the heat and reduce the temperature within the dwelling, thereby ensuring that re-ignition would not occur. The plastic buckets used for this test can be purchased from a local hardware store for approximately US$ 4 per bucket.

3.5.3.2. Mass Application

In contrast to the bucket brigade test utilizing a continuous supply of water buckets, this test focuses on supplying a larger amount of water at a reduced frequency i.e. several buckets are filled with water before being passed towards the dwelling where they are then applied to the fire in quick succession. This was done to answer the question: when communities extinguish a fire should one bucket at a time be applied, or should residents wait until several buckets are ready and then apply them all at once? Once all the buckets of water have been applied to the fire, the buckets are then passed back towards the tap where the process is then repeated. For this test four 8 litre buckets were filled at a given time before being passed over an approximate distance of 20 m towards the fire.

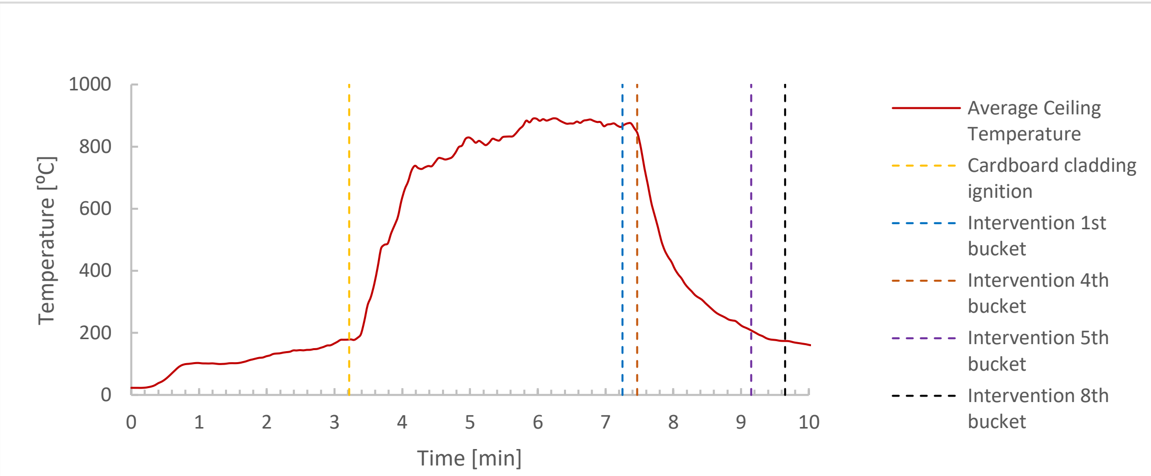

Figure 3.14: Time-temperature curve - Bucket brigade test (mass application)

The first bucket of water was applied to the fire approximately 7.3 minutes after ignition which is illustrated in Figure 3.15. The next three buckets of water were applied to the fire within 14 seconds after the application of the first bucket. The first two buckets of water were directed towards the left side of the dwelling (with respect to the door opening), whereas the third and fourth buckets of water were aimed at the right side of the enclosure. After the application of the first two buckets there were no visible flames emerging from the left half of the dwelling which was also applicable for the right side once the third and fourth buckets of water were applied. Thereafter, the four buckets were carried back to the tap where they were refilled. During this time minor re-ignition in the far-left corner of the dwelling was observed. The second series of four buckets was applied to the fire between 9.2 and 9.7 minutes after ignition. The application of the second series of buckets successfully doused the remaining flames in the remote corners of the dwelling and reduced the temperature within dwelling. Thereafter, no re-ignition occurred within the dwelling and the test was terminated.

Figure 3.15: Application of Bucket Brigade.

3.5.4. Non-water-based interventions

Due to the lack of water available in some settlements, or the distance from homes to water supply points, municipalities have had many proprietary products marketed to them which inhabitants can use to extinguish fires. The suitability of such products in post-flashover environments has historically not been addressed, making it difficult for decision-makers to assess their effectiveness.

3.5.4.1. DCP Fire Extinguisher

Dry chemical powder (DCP) fire extinguishers are multi-purpose mobile fire extinguishers which are suitable for Class A, B and C fires. The extinguishing agent contained within the cylinder is a fine chemical powder which comprises of a mixture of monoammonium phosphate and ammonium sulphate, the former acting as the active agent and can be purchased for approximately US$ 50 depending on the supplier. Similar to the previous tests, the cardboard insulation around the window opening ignited at 2.8 minutes, which initiated flashover shortly after, which is reflected by the sudden spike in the average roof temperature illustrated in Figure 3.16.

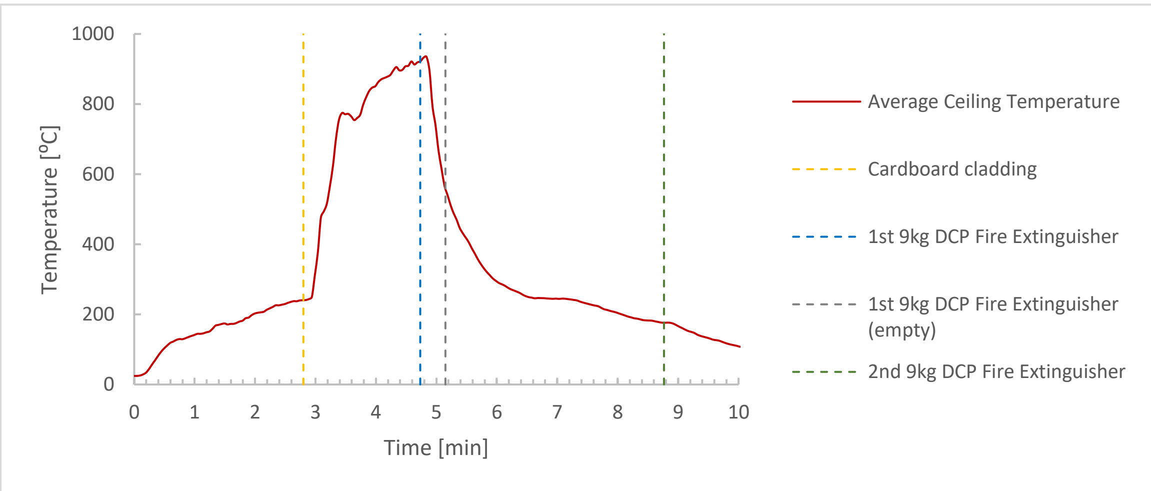

Figure 3.16: Time-temperature curve - DCP fire extinguisher test.

At approximately 4.7 minutes the firefighter initiated the intervention phase of the test by attempting to douse the fire with a 27A/144B fire rated 9 kg DCP fire extinguisher [24]. The extinguishing agent was directed through the door opening towards all areas of the enclosure. Shortly, after the DCP fire extinguisher was applied one could observe how the extinguishing agent displaced the combustion gases within the dwelling forcing them out of the window and door opening, which is illustrated in Figure 3.17, thereby causing an immediate heat reduction within the dwelling. The extinguishing agent within the fire extinguisher was depleted 30 seconds after its initial application. Once, visibility was restored only minor flames in the far-right corner of the dwelling were observed.

Figure 3.17: Application of DCP fire extinguisher.

Thereafter, it was decided to wait a couple of minutes before applying the next fire extinguisher in order to identify whether re-ignition would occur. After 3.5 minutes no significant change in terms of re-ignition was observed and therefore the second 9 kg DCP fire extinguisher was used to fully extinguish the fire. It should be noted that only half of the second DCP fire extinguisher was required before the fire was fully extinguished.

3.5.4.2. Fire ball dry chemical powder unit

The fire ball dry chemical powder unit is a relatively modern “grenade-style” fire extinguishing device which is based on technology originating from the 19th century [25]. Unlike its 19th century counterpart, the modern-day fire extinguishing ball consists of an expanded polystyrene (EPS) foam shell, internal agent drive system and monoammonium phosphate powder (also known as ABC dry chemical powder). Upon contact with a naked flame, the fuse which is placed around the EPS foam shell is ignited which activates the internal drive device containing a small black powder charge. Once the black powder charge has been activated, the internal drive system triggers a rapid expansion of the fire ball, thereby causing the EPS foam shell to disintegrate, which releases and disperses the dry chemical powder. The unit price ranges between US$ 40 – 110 depending on the retailer. The fire ball has a 1A/5B fire rating and is designed for pre-flashover compartment fires with a volume of approximately 3 m^3 whereas the representative test structure has a volume of 20.7 m^3 [26].

Although the fireball is not designed to suppress large post-flashover compartment fires, they are being purchased by municipalities for post-flashover fires and therefore its performance for post-flashover compartment fires was tested. Figure 3.18 illustrates a conceptual drawing of the fire ball extinguishing unit used during this investigation.

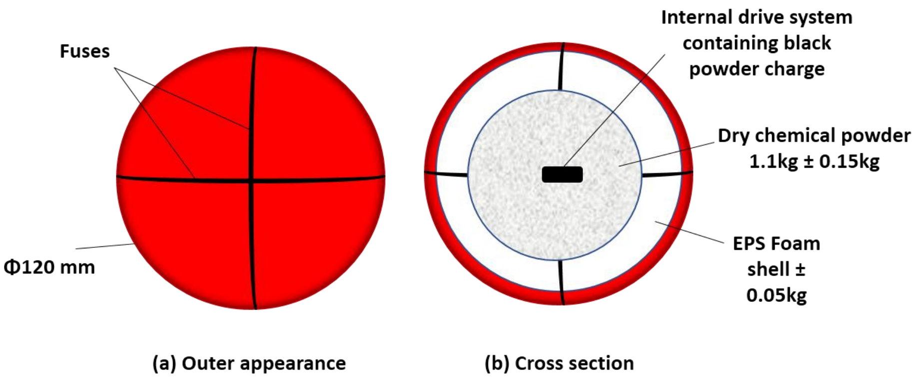

Figure 3.18: Conceptual drawing of fire ball dry chemical powder unit (a) outer shell (b) cross-section

For this test, fully developed conditions were achieved approximately 5.8 minutes after ignition which signalled the start of the intervention phase. Firstly, it was of interest to observe the suppression ability of a single unit. It is important to note that all units were directed into the dwelling through the door opening from a distance of approximately 3 m. The time-temperature behaviour for the test is depicted in Figure 3.19.

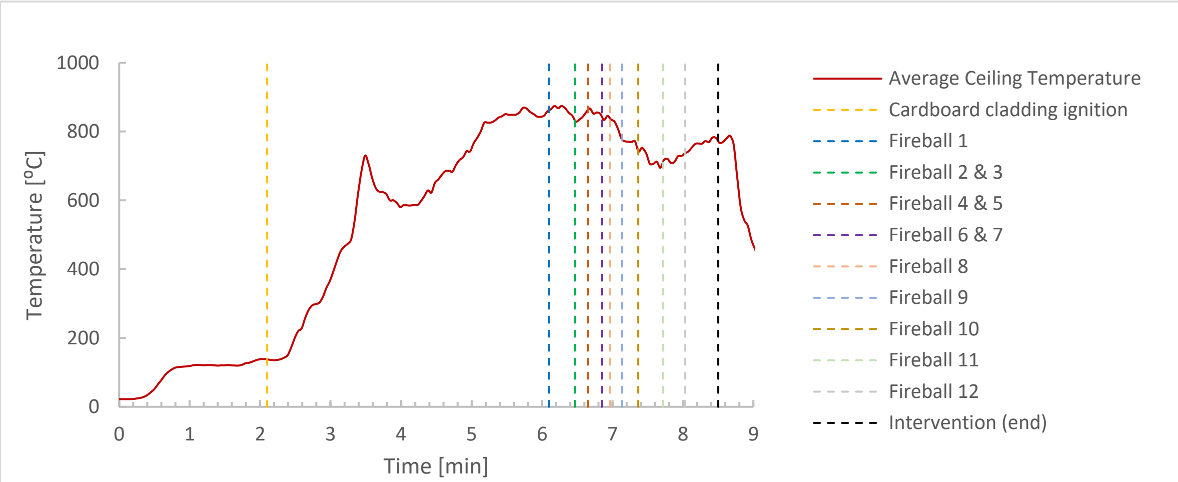

Figure 3.19: Time-temperature behaviour – Fire ball DCP unit test.

The first unit was directed into the dwelling 6.1 minutes after ignition. Once the unit had been deposited into the dwelling a couple of seconds were required for the fuse to activate the internal drive system which then released the dry chemical powder. Following the detonation of the first unit, no visible changes were observed within the dwelling in terms of flame reduction, which is also represented by a steady temperature behaviour in Figure 3.19. Thereafter it was decided to apply two units at a given time to observe the effect thereof. The second and third units were directed into the dwelling at 6.5 minutes. Upon detonation, localized displacement of the combustion gases where the units had been thrown was observed. However, within seconds the fire re-established itself and sustained its intensity. A total of 12 units were applied to the fire during which the same behaviour was observed. At 8.5 minutes after ignition it was decided to terminate the test and extinguish the fire by means of a firehose, which accounts for the sudden drop in the average roof temperature in Figure 3.19.

3.5.4.3. Throwable fire extinguishing unit

The throwable fire extinguishing unit is a modern approach at combating compartment fires. The lightweight throwable fire extinguishing proprietary unit comprises of an ampoule manufactured from plastic resin which contains the extinguishing agent. Figure 3.20 depicts a conceptual drawing of the throwable extinguishing unit utilized for this test. The extinguishing agent in the throwable extinguishing unit appears in liquid form and consists of organic and inorganic salts of which Potassium salt forms the main compound. The throwable extinguishing unit is suitable for Class A and B fires and achieves a 43A/233B fire rating [27]. In the event of a compartment fire, it can be thrown directly towards the source of the fire. Upon impact the plastic resin ampoule is designed to shatter, thereby releasing the extinguishing agent onto the flames. The unit price for the throwable fire extinguishing unit is approximately US$ 60.

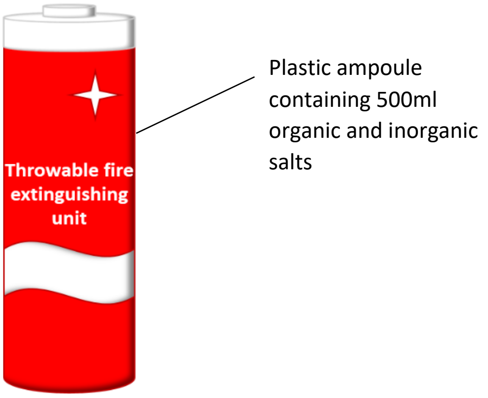

Figure 3.20: Throwable fire extinguishing unit.

During this test the throwable fire extinguishing units were directed through the door opening from an approximate distance of 4m. The first unit was thrown into the enclosure at 5.5 minutes after ignition. The application of the first unit did not influence the intensity of the fire and therefore it was decided to direct additional units into the dwelling at regular intervals. The fifth unit was applied at approximately 5.9 minutes after ignition. The first 5 units were directed towards the back end of the dwelling during which no significant visible changes were observed. The following 5 units were applied both to the back as well as the front of the dwelling, where the tenth unit was introduced at roughly 6.4 minutes after ignition. When the throwable extinguishing units were directed to the front of the dwelling a temporary localised reduction in flame height was observed at the point of impact. However, re-ignition was observed within a minute after the unit was applied. This behaviour was observed throughout the duration of the experiment. After the application of the 24th unit, the fire continued to sustain its intensity and therefore it was decided to terminate the experiment at 10.0 minutes after ignition.

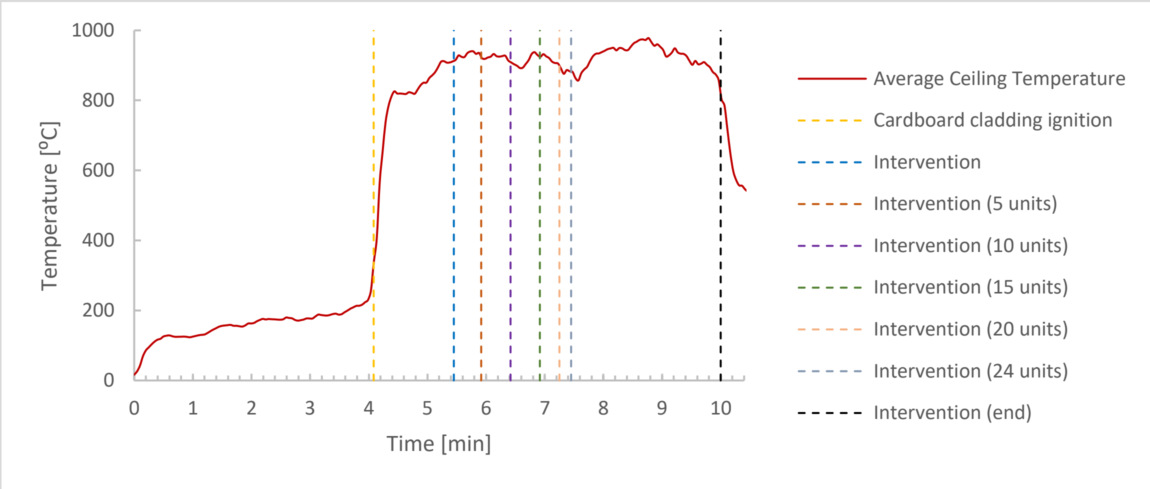

Figure 3.21: Time-temperature curve - Throwable fire extinguishing unit test.

3.6. Evaluation and Discussion

Table 3.2 provides a summary of various important experimental parameters such as the maximum temperature encountered during testing, maximum average roof temperature, average roof temperature decrease experienced during the suppression phase, intervention duration and the amount of product used. With reference to the individual time-temperature curves it can be seen that the early fire development within the enclosure can vary significantly from one another. Some of the factors responsible for the difference in early fire development include wind conditions, since the tests were performed over five days and flame impingement onto the cardboard occurred at different time, which initiated flashover. However, the steady-state temperature or fully-developed conditions are the main focus, since this research's focal point is centred around post-flashover fires and therefore the discrepancies in early fire development behaviour are not substantial for this research.

Table 3.2: Summary of important experimental parameters

Test	Max temperature	Max avg. roof temperature	Roof temperature decrease	Intervention duration	Product used
Water Jet	869 ^{o}C	833 ^{o}C	556 ^{o}C	1 min 0 sec	100 litres water
NAFS	946 ^{o}C	897 ^{o}C	749 ^{o}C	1 min 13 sec*	320 litres water 3.2 litres concentrate
CAFS	895 ^{o}C	860 ^{o}C	766 ^{o}C	51 sec*	240 litres water 0.96 litres concentrate
Bucket Brigade (continuous)	925 ^{o}C	890 ^{o}C	737 ^{o}C	2 min 58 sec	72 litres water
Bucket Brigade (mass)	922 ^{o}C	891 ^{o}C	718 ^{o}C	2 min 24 sec	64 litres water
DCP fire extinguisher	964 ^{o}C	935 ^{o}C	770 ^{o}C	4 min 12 sec	1.5 x 9kg fire extinguisher
Fireball	899 ^{o}C	875 ^{o}C	93 ^{o}C	2 min 24 sec	12 units
Throwable extinguishing unit	1013 ^{o}C	978 ^{o}C	120 ^{o}C	4 min 33 sec	24 units

*Due to visibility restrictions during the suppression phase it was not possible to determine the exact time at which the fire was extinguished and therefore in reality the actual intervention duration would be a bit shorter than indicated.

As stated in the beginning of this paper, the goal of this investigation is to develop a full-scale testing methodology for benchmarking the performance of various existing active fire suppression systems for post-flashover informal settlement fires, using the products tested to illustrate how different systems perform in relation to one another. The selected interventions will be evaluated according to the analytical hierarchy process (AHP), which will be utilized to quantify the respective weightings of each criteria based upon a pair-wise comparison of each intervention. The AHP is utilized in this investigation, since it allows for the problem at hand to be decomposed into a series of sub-problems, which can be analysed independently. The following criteria are considered while evaluating the respective interventions:

Effectiveness:

The efficacy of the tested interventions will be evaluated based on the intervention's ability to reduce the flames within the enclosure as well as the heat reduction measured within the enclosure and by considering whether the intervention is capable of preventing re-ignition from occurring, once the fire has initially been knocked down.

Efficiency:

The efficiency of the tested interventions will be assessed by considering the relative capital and maintenance costs of each intervention as well as the costs associated with the amount of product consumed during the suppression phase. It should be noted that the feasibility of the associated costs is determined assuming that the municipality would have to fund the respective products/systems, since the residents are unable to afford the proposed interventions due to their financial status.

Appropriateness:

The appropriateness of the tested interventions will be evaluated based upon its ease of use (does it require specialized equipment and/or trained personnel?), first response time, availability (how commercially available is a certain product/service?), biodegradability of the suppressant used, as well as potential identifiable issues pertaining to the large scale implementation (includes factors such as reduced application rate, reachability and accessibility etc.).

The proposed AHP model along with the weighting of the individual criteria is presented in Figure 3.23.

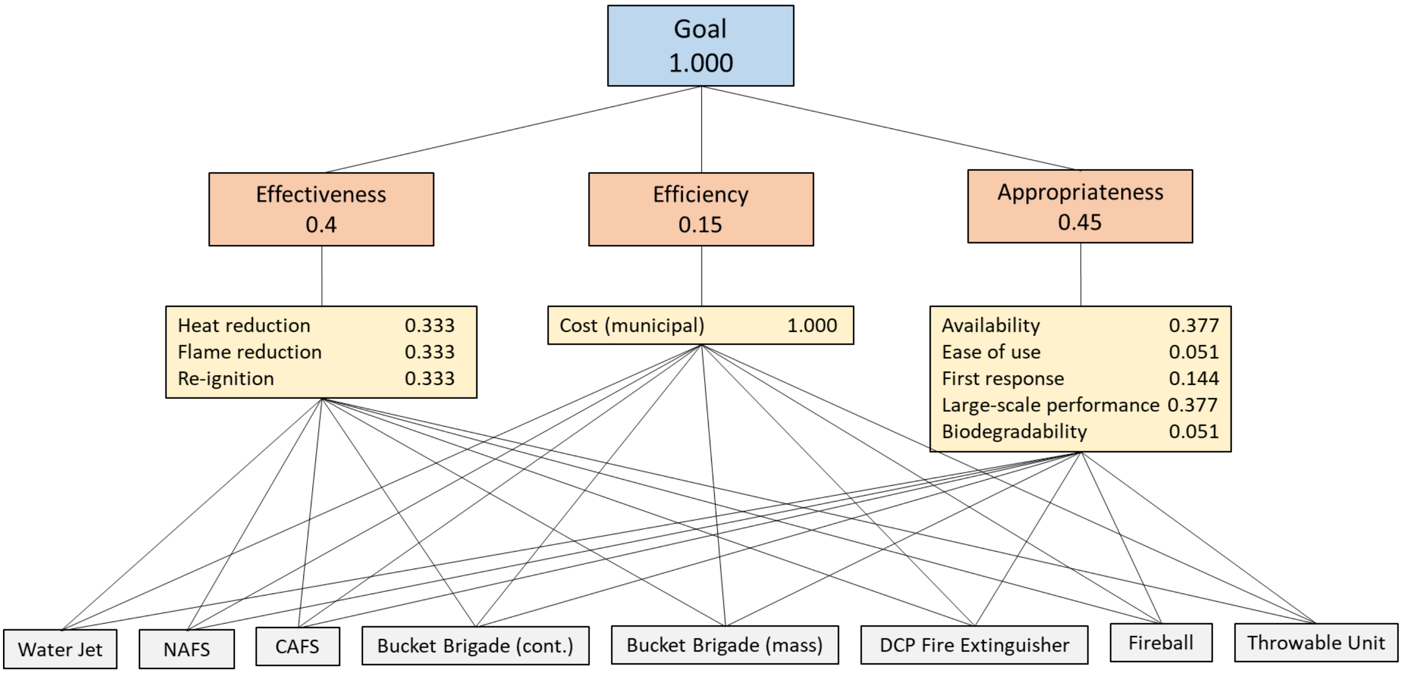

Figure 3.23: AHP model including weighting of each criteria.

To compare the effectiveness of the various active fire suppression products and suppression techniques, it is necessary to normalize the individual time-temperature curves and combine them into a single figure, from which an accurate comparison can be drawn. Figure 3.22 depicts the normalised time-temperature responses of the various tests following the initiation of the intervention process until the tests were terminated.

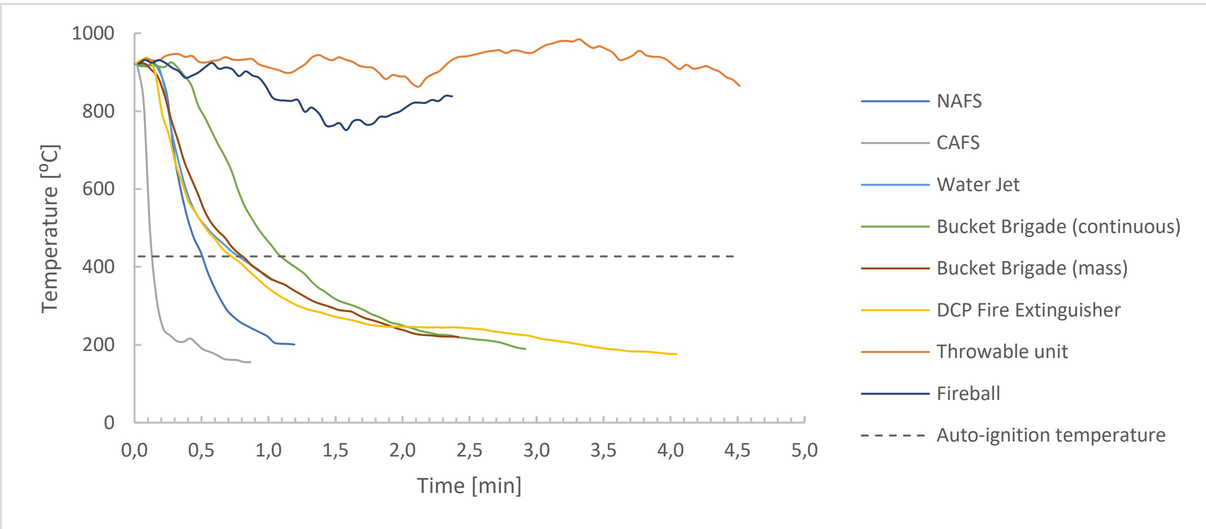

Figure 3.22: Normalised time-temperature behaviour comparison of tested interventions.

With reference to Figure 3.22 it can be observed that the water-based suppression products successfully extinguished the fire, while simultaneously reducing the temperature within the enclosure, thereby preventing re-ignition from occurring. An almost immediate drop in the average roof temperature within the dwelling can be observed, once the water-based suppression products were applied to the fire, since the heat released from the combustion reaction is absorbed by the water. The delay between the time of intervention and the temperature reduction within the dwelling for the water-based interventions arises due to the thermocouples being situated along the ceiling of the enclosure while the water was often not immediately directed towards the ceiling, thereby resulting in a delayed response.

Water as a suppression agent extinguishes a fire by combining two principles simultaneously. Firstly, upon application the water vaporizes as it interacts with the fire. The formation of water vapour consequently smothers the fire, since the volume of water vapour is 1700 times greater than that of water in its liquid phase and therefore displaces the oxygen required to sustain the combustion reaction [28]. In addition to steam smothering, water also extinguishes a fire by absorbing the heat released from the combustion process, thereby providing a cooling effect to the surrounding smoke, air, objects and compartment boundaries. One of the objectives of firefighting is to decrease the temperature to a point at which pyrolysis cannot occur and halting the combustion reaction of the fuel. Therefore, the steam will have to absorb enough energy to lower the temperature within the enclosure until the temperature within the enclosure is lower than the auto-ignition temperature of the fuel. For the purpose of this research investigation the auto-ignition temperature of pine is approximately 427 ^{0}C [29].

3.6.1. Brigade-based interventions

The water jet, NAFS as well as the CAFS tests all successfully doused the fire shortly after the intervention phase was initiated which is reflected by an almost immediate decline in the average roof temperature depicted in Figure 3.22. During the water jet test, a total of ±100 litres of water was used from the point of intervention until the test was terminated. However, it should be noted that more water was applied afterwards to further cool down the dwelling in order to reduce the waiting period required to setup the following test.

With reference to Figure 3.22 it becomes apparent that there is an almost immediate decline in the temperature experienced within the dwelling following the intervention of the NAFS. In addition to the cooling ability of NAFS which results in the heat reduction within the dwelling, the foam solution blankets the fuel source, thereby separating the fuel from the fire and preventing re-ignition from occurring. During the experiment a total of 3.2 litres of foam concentrate and ±320 litres of water was consumed.

The introduction of the hose during the CAFS test, resulted in an instantaneous heat reduction and the fire was extinguished approximately four seconds following the introduction of the hose. Thereafter, there were no visible flames within the enclosure which resulted in a rapid decline in the temperatures experienced within the dwelling. This correlates with Figure 3.22, where an instantaneous temperature reduction is documented as soon as the CAFS is introduced. The resulting rapid heat reduction within the dwelling occurs due to several factors. Firstly, the concentrated air foam mixture adheres to the boundaries of the enclosure which in turn results in a significant heat reduction within the compartment, due to the reduction of radiative heat transfer. Secondly, the foam layer acts as a protection blanket for the fuel which starves the combustible fuel within the enclosure from any available oxygen. Lastly, the foam shields the fuel sources within the enclosure from radiation. Overall, a total of ±240 litres of water and 0.96 litres of foam concentrate were applied to the fire before withdrawing the hose from the enclosure.

A comparison of the time-temperature behaviour following the time of intervention for the water jet, NAFS and CAFS test is depicted in Figure 3.24 from which it can be seen that CAFS is the most effective at suppressing the fire. CAFS consumed 25% less water than the NAFS test which is an important factor when combating informal settlement fires where multiple dwellings are affected, since the extinguishing foam can be applied to more dwellings before it is depleted. The NAFS and CAFS test provide an additional measure of protection through the presence of the foaming agent which provides a cooling effect while forming a protective layer between the fuel load and the fire. One problem identified with all three methods is that the methods require the use of a vehicle to gain access to the affected dwellings which could potentially be a problem in informal settlements where accessibility to the dwellings might be hindered by narrow as well as obstructed roads and overhanging electrical. Furthermore, the use of CAFS is currently limited to municipalities with larger annual budgets, due to the high capital costs associated with CAF units. As a result, CAFS are predominantly used in metropolitan areas where the unit is shared amongst several fire departments. A further problem linked with CAFS is that the flow of foam solution does not like to be restrained within the hose line. In the event where the flow of the foam solution is restrained, for example by closing the nozzle, the foam within the hose is held back which results in a watery mixture when the nozzle is re-opened. This means it is difficult to stop the flow during firefighting operations. Once the nozzle has been fully opened the concentration of the foam solution will gradually be restored to its design value. This change in concentration will impact the extinguishing ability of the foam solution and should be considered when combating enclosure fires. Such practicalities mean that although the CAFS may require less water than the water jet and NAFS for a specific fire size, for overall firefighting operations they may require more water due to the inability to stop the flow when not needed. Lastly, it should be noted that the CAFS unit utilized was oversized for the firefighting operation and better results could be obtained by using a smaller unit where the flow can be regulated more effectively.

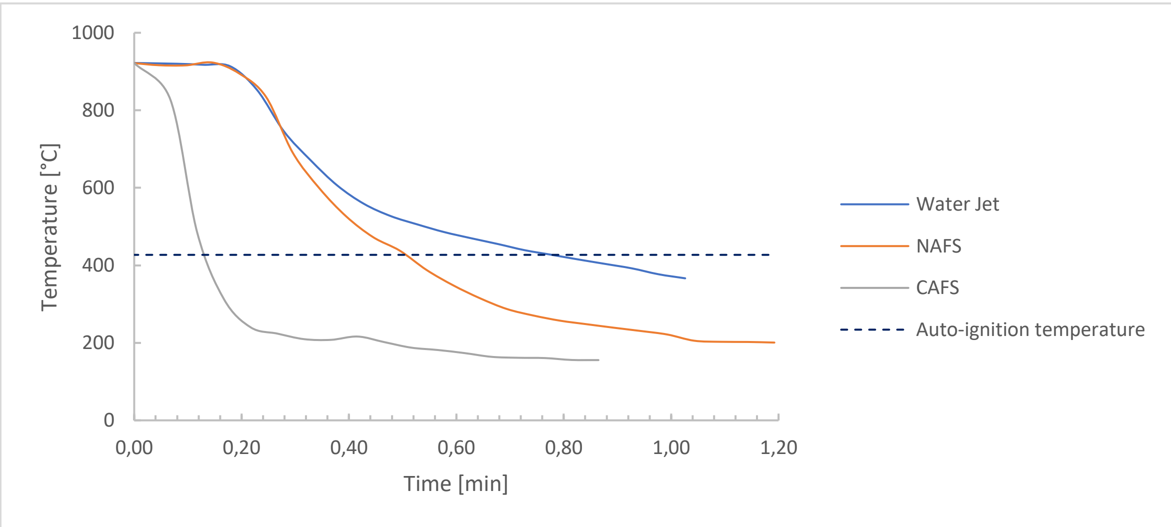

Figure 3.24: Normalised time-temperature behaviour comparison post-intervention (brigade-based interventions).

3.6.2. Community-based interventions

When comparing the bucket brigade tests it becomes evident that both methods successfully extinguished the fire and reduced the temperature within the dwelling to well below the auto-ignition temperature of the timber. However, upon closer inspection it becomes apparent that the bucket brigade test which utilised the mass application approach resulted in a more rapid initial temperature reduction than the bucket brigade test with the continuous application approach, as would be expected. The rapid initial reduction in temperature occurs due to the larger volume of water applied to the fire which in turn allows for greater heat absorption, thereby providing the cooling effect which lowers the temperature within the enclosure. A comparison between the temperatures recorded within the dwelling after the application of the 4th and 8th bucket of water for the mass application as well as the continuous application approach is depicted in Figure 3.25. With regards to Figure 3.25,

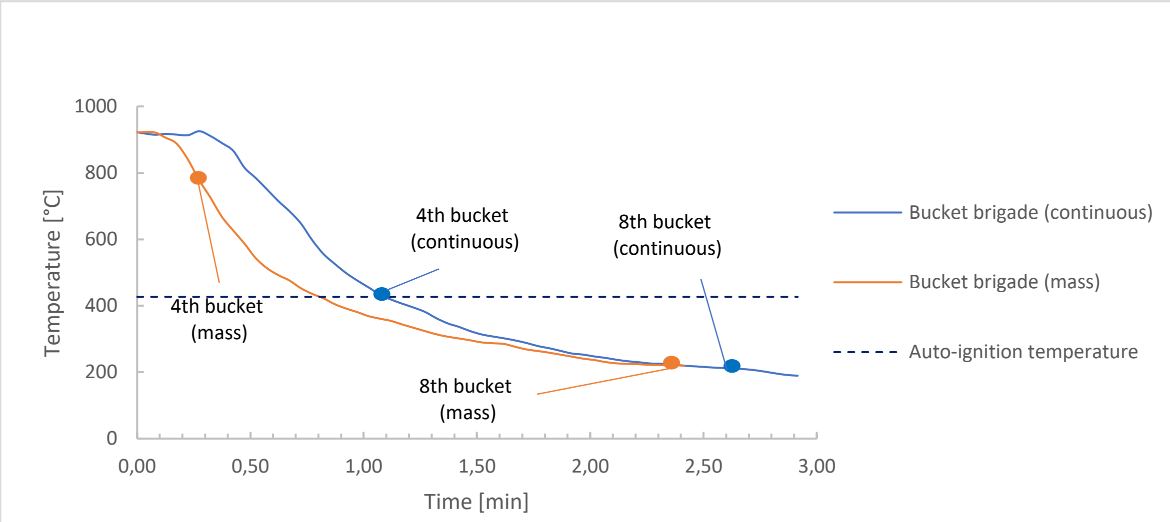

Figure 3.25: Normalised time-temperature behaviour comparison post-intervention (bucket-brigade interventions).

the immediate temperature reduction can be identified for the mass application approach and it becomes evident that the mass application approach lowers the temperature within the dwelling below the auto-ignition temperature of the timber faster than the continuous approach.

Although both bucket brigade tests were effective at suppressing the compartment fire it should be noted that the effectiveness of the methods is inversely proportional to the amount of dwellings affected by the fire, since more residents will have to use the same standpipe to fill their buckets with water, which in turn will increase the circulation time between the application of successive buckets.

3.6.3. Non-water-based interventions

The DCP fire extinguisher, fire ball DCP unit as well as the throwable extinguishing unit were the only non-water-based interventions tested in this research investigation. Of these three products the DCP fire extinguisher was the only product which successfully suppressed the fire, which is reflected in Figure 3.26.

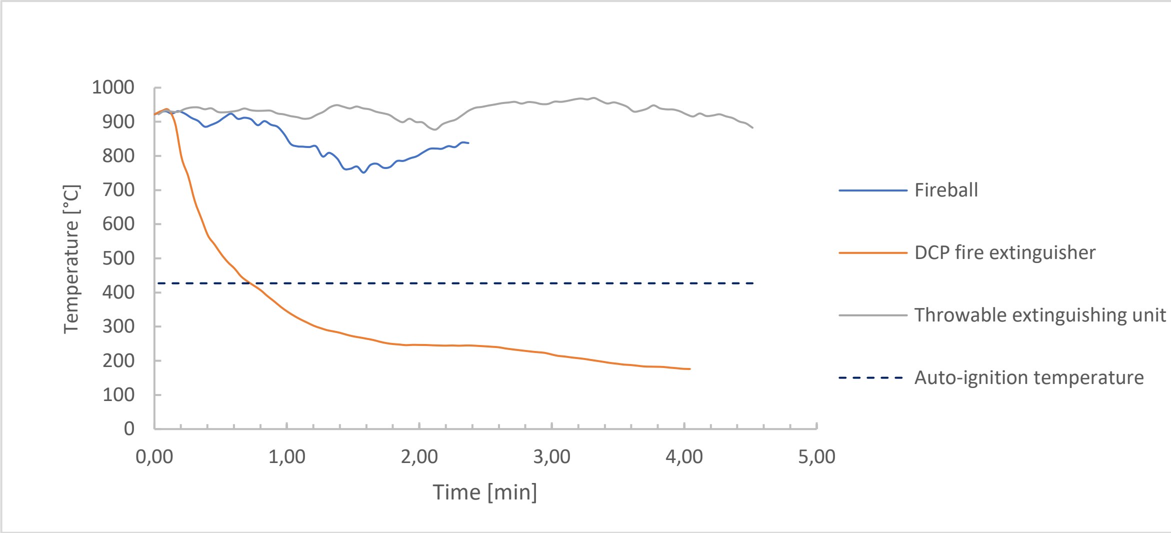

Figure 3.26: Normalised time-temperature behaviour comparison post-intervention (non-water-based interventions).

The DCP fire extinguisher test and the fire ball DCP unit test both utilized dry chemical powder as the suppression agent. However, the test utilising the DCP fire extinguishers successfully extinguished the fire, while the fireball test had little to no effect on the flames within the dwelling. Following the fire ball DCP unit test, an experiment was conducted on the dry chemical powder contained within the foam shell of the fireball to establish its performance when exposed to a naked flame. For this test a piece of timber was coated with the dry chemical powder contained within the fireball. The powder was then subjected to a naked flame from a blowtorch to identify whether the powder protects the underlying timber. After being subjected to a naked flame for approximately 30 seconds the flame was withdrawn, and the dry chemical powder was removed from the timber. Once the dry chemical powder was removed from the timber there were no signs of charring along the tested piece of timber which implies that the dry chemical powder does form an insulated layer between the fuel and the flame. During the full-scale testing a significant difference between the DCP fire extinguisher and the fireball was identified, namely, the dry chemical powder from the fire extinguisher adhered to the surfaces of the timber cribs where it then melted and formed an insulated layer over the fuel packages, thereby separating the fuel from any available oxygen and preventing the combustion process from being sustained. In contrast to the DCP fire extinguisher, the dry chemical powder contained within the fireball was merely distributed throughout the enclosure without adhering to any surfaces. This difference is shown in Figure 3.27. In contrast to the DCP fire extinguisher test, during the fireball test the majority of the dry chemical powder accumulated on the floor of the enclosure, therefore having minimal impact on the fire.

Figure 3.27: Wooden cribs after DCP fire extinguisher test (left hand side) and wooden cribs after fire ball DCP unit test (right hand side).

During the full-scale testing of the throwable extinguishing unit it was noted that 2 of the ampoules did not shatter upon impact and therefore did not release the suppression agent which is intended to inhibit the combustion reaction. It was observed that there was no significant change in terms of the flame intensity experienced within the dwelling once the unit was applied. Only localised effects were observed. However, it was identified that the fire re-established itself shortly after if left unattended.

3.6.4. Summary

As previously mentioned, the AHP will be utilized to quantify the weightings of the respective evaluation criteria, based upon a pair-wise comparison of the tested interventions. The weightings obtained using the AHP will form the basis for the overall evaluation of the tested interventions and will take into account the primary criteria of assessment (effectiveness, efficiency and appropriateness). A summary of the normalized weightings for the respective criteria is depicted in Figure 3.28. The weightings depicted in Figure 3.28 were obtained by performing a pair-wise comparison between the respective tested interventions, which considers the performance of the tested interventions based upon visual observations as well as data gathered during the execution of the full-scale experimental tests. The evaluation of the heat reduction criteria is primarily determined based on the rate of heat reduction measured at roof level following the initiation of the intervention phase, while the evaluation of the flame reduction criteria is based on visual observations documented during experimental testing and takes into account whether the introduction of the suppression agent leads to no change in terms of flame intensity, localized reduction of flame intensity, significant reduction or complete suppression of the flames. The same applies for the criteria of re-ignition, where the weighting is based on the relative degree of re-ignition following the initiation of the suppression phase. As previously discussed, the evaluation of the cost criteria is based upon the relative costs incurred to the municipality and accounts for factors such as capital, maintenance as well as operational costs, where a high rating (rating of 1.0) indicates the most financially feasible option.

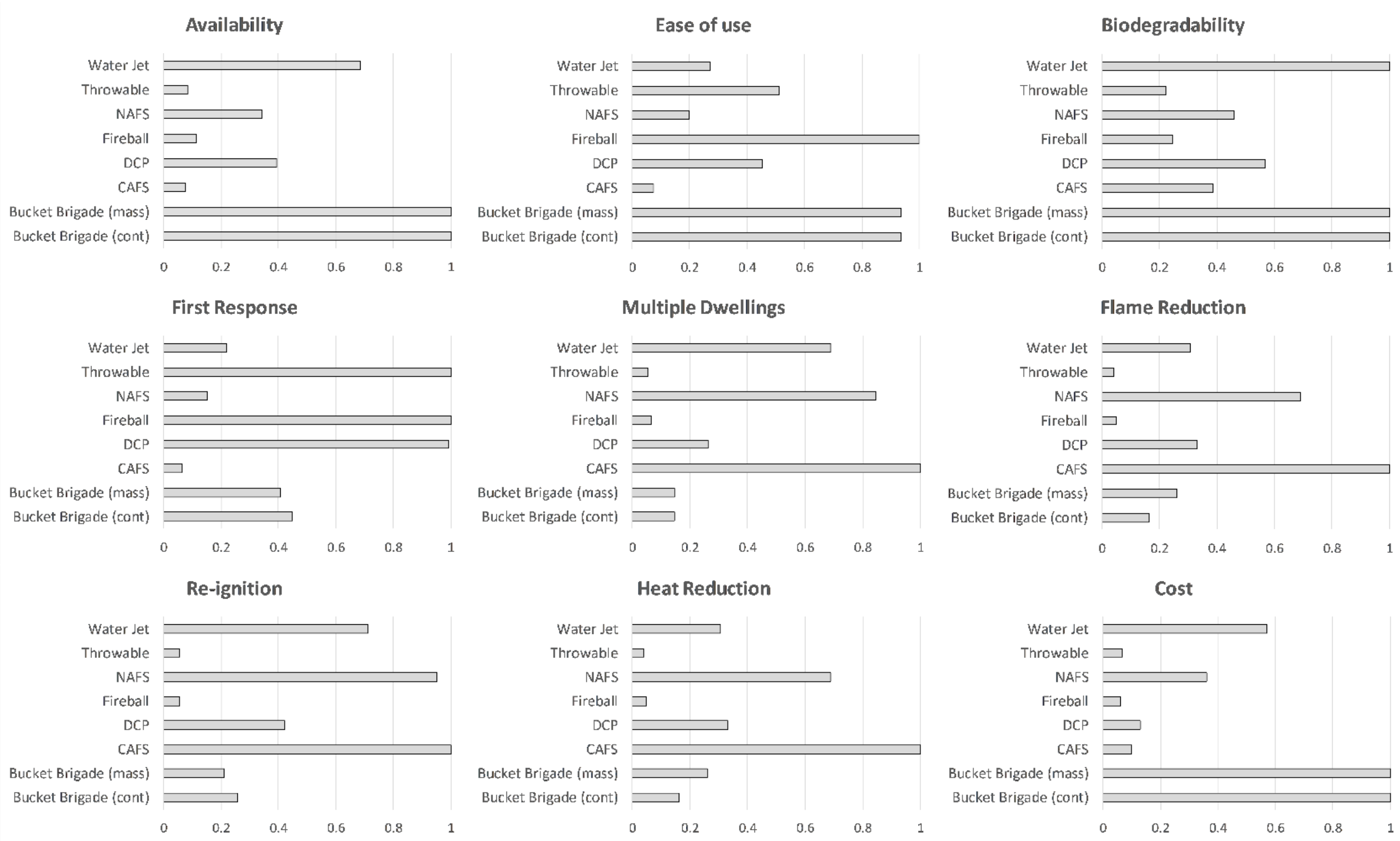

Figure 3.28: Normalized weighting of respective evaluation criteria based on a pair-wise comparison utilizing the AHP model.

For the evaluation of the "availability" criteria it was considered how commercially available the respective tested interventions are, since some of the interventions are limited to municipalities in urban/metropolitan environments and cannot be implemented in smaller/rural communities, while other interventions are limited in terms of local availability and need to be imported. The "ease of use" criteria considers whether skilled personnel or specialized equipment/training is required to use the proposed intervention. Some of the tested intervention such as the water jet, NAFS and CAFS require specialized equipment as well as trained personnel and are therefore limited to fire brigades. The time required to arrive at the scene of the fire and intervene is considered when evaluating the tested interventions with regards to the "first response" criteria. "Biodegradability" considers the effect of the suppression medium on the surrounding environment, for instance if the suppression medium has an adverse effect on species if it infiltrates nearby water bodies.

Lastly, the "large scale implementation" criteria accounts for any potential identifiable issues associated with the large scale implementation in informal settlements, which includes factors such as reduced application rate, limited reachability and accessibility to dwellings as a result of fire spread and limited access roads. Accessibility is an important factor for interventions such as the water jet, NAFS and CAFS, which require the use of a vehicle to gain access to the affected dwellings. Access roads in informal settlements are often obstructed by dwellings which encroach onto the roads. Accessibility is often also restricted due to overhanging electrical wiring.

3.7. Conclusion

This paper set out to develop a full-scale testing methodology for benchmarking the performance of various existing active fire suppression systems for post-flashover informal settlement fires. A total of nine full-scale experiments were conducted which investigated the suppression ability of selected brigade-based, community-based as well as non-water-based interventions. During testing it was observed that the water-based suppression products were highly effective at suppressing the fire within the enclosure while simultaneously cooling the compartment, since the water absorbs the heat released from the combustion reaction. The use of DCP fire extinguishers proved to be highly effective at extinguishing the fire within the representative dwelling and ensuring that re-ignition would not occur, however, the limited reach and high unit cost as well as the annual maintenance costs pose potential limitations in terms of full-scale implementation. The two throwable extinguishing products, namely the fire ball DCP unit and the throwable extinguishing unit were both unsuccessful at suppressing the fire or reducing the temperature within the dwelling and are therefore not suitable for post-flashover compartment fires. Based on the discussion regarding the performance of the various active fire suppression systems utilized throughout the full-scale testing, the evaluation thereof is summarised in Figure 3.29 and Table 3.3 which are based upon the pair-wise comparison of the AHP model. The normalized rating for each of the tested interventions was determined based on the three primary categories of evaluation, which were addressed above. The results of the AHP model may vary depending on factors such as the budget allocated towards municipalities, which in turn will influence the viability of certain interventions. Municipalities of smaller communities or municipalities with smaller annual budgets may therefore not be able to afford NAF or CAF systems and would therefore have to consider other alternatives. Other factors which would have to considered by the individual municipalities include the time required to fill and transport the buckets of water from the water source to the affected burning dwelling.

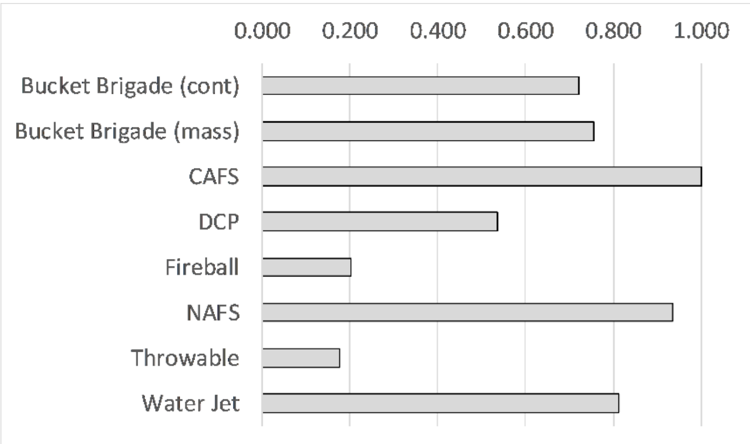

Figure 3.29: Summary of the normalized results obtained from the AHP model.

Table 3.3: Ranking of tested interventions showing fire brigade based interventions in red and community based interventions in blue.

Intervention	***Normalized Rating***	***Rank***
CAFS	1.000	1
NAFS	0.936	2
Water Jet	0.816	3
Bucket Brigade (mass)	0.759	4
Bucket Brigade (cont.)	0.720	5
DCP	0.536	6
~~Fireball *~~	~~0.204~~	~~7~~
~~Throwable *~~	~~0.177~~	~~8~~

*Interventions did not succeed in suppressing the fire and should therefore not be considered in the ranking of this investigation as suitable for large-scale implementation

The testing methodology presented in this paper provides an example of how different products can be benchmarked against one another, thereby providing an initial indication on what might be feasible. The testing method and results from these sorts of tests could be adopted as a decision-making tool by the respective authorities thereby potentially preventing costly investments in products or systems that are not suitable for the cause. While many of the interventions tested throughout this investigation were highly effective at suppressing the fire it should be noted that each intervention possesses its own limitations and difficulties which include but are not limited to the financial feasibility in terms of large-scale implementation into informal settlement communities, maintenance costs, community acceptance, first response times, vandalism etc. Based on the findings from this investigation, further work would have to be conducted to establish the effectiveness of the tested active fire suppression products for multi-dwelling fires.

3.8. Acknowledgements

The authors would like to gratefully acknowledge Epping Fire and Rescue Training Academy, especially Mr C Manuel, Mr F Munnik and his team, for their contribution and assistance towards helping the authors successfully complete the tests. Additionally, the authors would like to take the time to thank Zara Sander for assisting with the logistics, set-up and executing of the tests. This work has been assisted by the Western Cape Disaster Management, Fire & Rescue Services. The authors would like to acknowledge the financial support of the Lloyd's Register Foundation under the "Fire Engineering Education for Africa" (FEEFA) Grant.

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Chapter 4: Determination of water application rates required for communities to suppress post-flashover informal settlement fires based on numerical modelling and experimental tests

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Submitted to: Fire and Materials

Declaration by the candidate:

The nature and scope of the candidate's contribution were as follows:

Nature of contribution	Extent of contribution (%)
i. Execution of modelling work ii. Analysis of numerical modelling output iii. Preparation of manuscript iv. Data Analysis	90%

The nature and scope of the co-author contribution were as follows:

Nature of contribution	Extent of contribution (%)
i. Supervision and guidance of the work ii. Revision of the manuscript	10%

Signature of candidate: Stefan Löffel
Date: 27 September 2019

The undersigned hereby confirm that:

The declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-author to Chapter 4.

No other authors contributed to Chapter 4 besides those specified above, and

Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4 of the thesis

Signature	Institutional affiliation	Date
Stefan Löffel	Stellenbosch University	27 September 2019
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This chapter is an exact copy of the journal paper referred to above

Contribution of chapter to thesis

Chapter 4 focuses on the development of various numerical models that have been produced and calibrated based on experimental results originating from Chapter 3. The numerical models developed in this chapter investigate the influence of water application rates and travelling distances between the burning dwelling and the water supply point on the suppression duration in order to determine whether it is possible for communities to suppress informal settlement fires of various sizes, based on the existing water supply infrastructure. Before the effectiveness of a wide variety of suppression products can be numerically tested it is necessary to develop models based on the simpler tests conducted, and upon validated principles in the literature. Additional research is required before all the products investigated in the previous chapter (especially such as CAFS and DCP fire extinguishers) can be simulated in FDS.

4.1. Abstract

Fires originating in informal settlements (i.e. slums, ghettos, shantytowns, squatter camps) spread rapidly, due to the presence of densely packed, highly combustible dwellings, thereby making these communities inherently susceptible to large conflagrations. By the time the fire brigades are notified and can get to the scene of the fire, the resulting conflagrations can be large. Thus, it is necessary to equip communities with the ability to combat smaller fires, although it is acknowledged that this is not ideal. Previous full-scale testing, and firefighter experience, have shown that water application through "bucket brigades" can be very effective at suppressing fires. In this paper a model is developed for approximately quantifying the amount of water, and discharge rate, that is required for communities to suppress fires of various sizes using bucket brigades. This is done to answer the question: based on the water supply infrastructure in an area could a community put out post-flashover fires of certain sizes? If this is not feasible, it would highlight the importance of communities having readily available pre-filled water buckets at homes. The model presented is developed in Fire Dynamics Simulator (FDS) and is calibrated based on full-scale experiments utilizing the bucket brigade technique. It is shown that standpipe discharge rates of 23 to 40 lpm are suitable for fire sizes of around 3.85 MW, based on a dwelling size of 2.4 x 3.6 x 2.4 m. This means that in communities with a single stand-pipe (water supply point) with flow rates less than 23 lpm, that fires greater than 3.85 MW (as produced by a home of 2.4 x 3.6 m with a timber fuel load of 25 kg/m^2) cannot be suppressed in time without resulting in substantial fire spread to adjacent dwellings.

KEYWORDS: Informal settlement fires, active fire protection, full-scale experiments, Computational Fluid Dynamics modelling, numerical modelling

4.2. Introduction

Africa is currently experiencing the fastest population growth in the world and there are no signs indicating that this trend is expected to decrease in the near future with Africa's population expected to increase from 1.31 billion to 2.53 billion by 2050 [1]. Along with the rapid population growth, African countries are forecasted to experience a substantial increase in the rate of urbanisation, with people migrating to cities in the search of employment opportunities. With the exponential population growth accompanied by the rate of urbanisation, the provision of formal housing and basic infrastructure such as electricity and running water, is often insufficient or of unsatisfactory standard, which results in the expansion of existing informal settlements as well as an increase in the formation of newly formed informal settlements across the continent. Consequently, the world will see an alarming increase in the number of people residing in informal settlements.

Informal settlements, also often referred to as slums, ghettos or squatter camps, are informal residential communities predominantly consisting of densely populated informal settlement dwellings (ISDs) that have been established on ground that has not been formally surveyed or proclaimed for residential use [2]. Residents within informal settlements generally suffer from abject poverty and therefore scavenge the materials required for the construction of their dwelling, since they are unable to afford the prices of new construction materials. As a result, residents typically construct their dwellings from any readily available materials within their proximity, which include materials such as timber planks, corrugated roof sheeting and various plastics, which promote fire growth and fire spread in the event of a fire [3]. Figure 4.1 depicts a schematic representation of a typical ISD and provides information regarding the layout and use of construction materials.

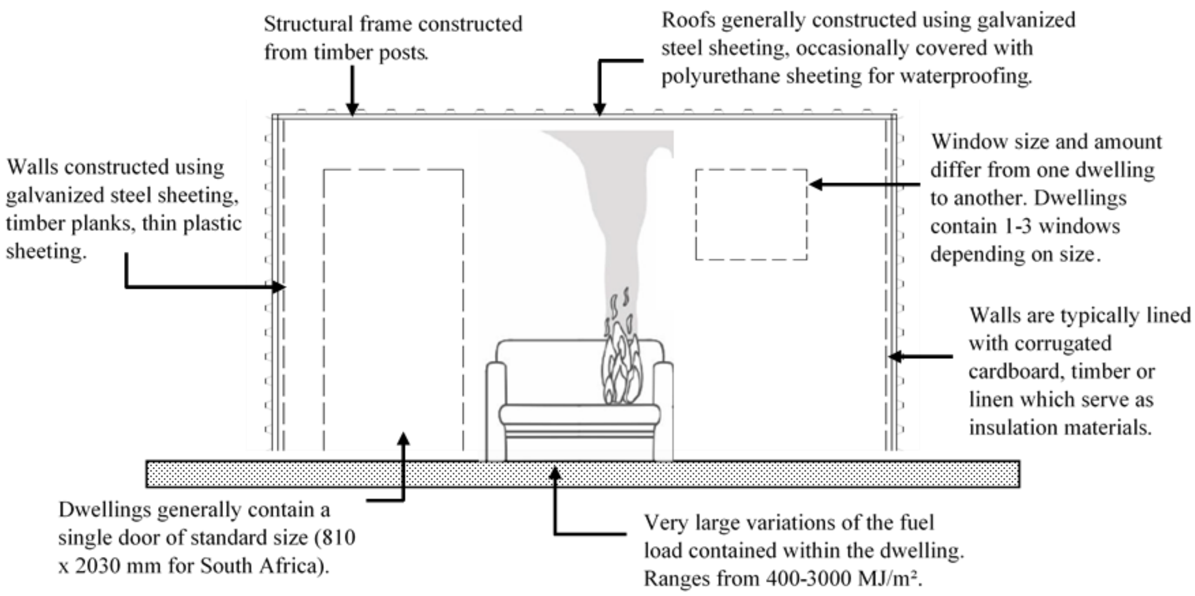

Figure 4.1: Details pertaining to the layout and construction materials of typical informal settlement dwellings.

Fires in informal settlements spread rapidly through the community as a result of the high dwelling densities within these areas and the highly combustible nature of the dwellings themselves. Table 4.1 highlights some of the informal settlement fires experienced within Cape Town, South Africa.

Table 4.1: Examples of informal settlement fire in Cape Town [5–11]

Date	Informal Settlement	Dwellings affected	People displaced	Fatalities
15-Jan-05	Joe Slovo	3000	12000	*No Fatalities*
28-Nov-15	Masiphumelele	800	4000	2
12-Mar-17	Imizamo Yethu	2194	10000	4
10-Jan-18	Joe Slovo	3000	12000	1
20-Oct-18	Silver Town	342	1355	1
25-Oct-18	Overcome Heights	309	842	*No Fatalities*
29-Aug-19	Masiphumelele	256	1280	1

By the time fire brigades are notified and arrive at the scene of the fire, the resulting conflagrations can be large. Thus, it is necessary to equip communities with the ability to combat smaller fires, although it is acknowledged that *this is not ideal, and done out of necessity rather than preference*. Previous full-scale testing, and firefighter experience, have shown that water application through "bucket brigades" can be very effective at suppressing fires [4]. The term "bucket brigade" refers to a technique which is often adopted by residents within informal settlements when attempting to suppress fires, where buckets are filled with water at a nearby communal standpipe and are then passed from one person to another until the bucket has reached the burning ISD. It is with this backdrop that this paper aims to develop a model for quantifying the amount of water, and supply rate, that is required for communities to suppress fires of various sizes using bucket brigades. This is done to answer the question: based on the existing water supply infrastructure in an area, could a community extinguish post-flashover fires of certain sizes? By developing computer models, validated through full-scale experiments, it will become easier to assess which fire suppression products and techniques may, or may not, be suitable for informal settlement fire safety. Ultimately full-scale testing will always be required for product validation, while computer models provide a cost-effective solution for initially comparing alternatives and assessing new proposals.

Although this work focusses on bucket brigades, the work could be extended in the future to be applied to the large variety of products available on the market (e.g. extinguishers, throwable products, dry chemical powders) as well as different suppression techniques utilized by fire fighters (e.g. foam systems, suppression tactics for multi-dwelling fires) and residents (e.g. using available materials, considering water supply systems, new products), thereby providing an effective methodology for assessing the fire suppression performance of various fire suppression products and techniques. Many products the authors have seen being sold to municipalities are unsuitable, except for very small fires, and numerical models could be used to reduce the number of costly tests required, whilst preventing unnecessary investments in unsuitable fire safety measures. Highly accurate results are not feasible in this work, considering the large number of variables inherent in informal settlements, but through parametric studies guidelines can be provided for what is feasible in this complicated, but essential, field of fire safety. This work has been developed specifically for conditions in South Africa, although would typically be applicable in many other low-income countries with similar housing conditions.

4.3. Experimental full-scale testing

A series of full-scale post-flashover tests were conducted at the Epping Fire and Rescue Training Academy in Cape Town, South Africa. Various suppression products and techniques were tested such as: water application via conventional firefighting hoses, compressed air foam systems, throwable proprietary products, dry chemical powder fire extinguishers, and the application of water through two bucket brigade techniques. This was done along with a full-burnout test used as a benchmark for comparison and validation. The purpose of the burnout test was to identify the nature of the fire development and to obtain a data set against which the other tests can be compared. By using the results from the burnout test it becomes possible to evaluate the suppression effectiveness of various tested interventions. Since this work seeks to understand water application rates required for community response it will only focus on the bucket brigade application tests.

For this test a representative ISD was designed and constructed based on the dimensions of the ISO 9705 room [12]. The only deviation from the ISO 9705 room was the addition of a 0.80 x 0.80 m window opening which was placed in the centre of one of the side panels. The frame of the structure was constructed from 32 x 3.0 mm square hollow steel tubing to ensure that the frame would not collapse during the execution of the experiment, thereby allowing for multiple tests to be conducted. The walls and roof consisted of 0.58 mm galvanized IBR steel sheeting. The dwelling was extensively equipped with Type K Thermocouples measuring the temperatures at various locations within the dwelling as well as at 1m, 2m and 3m from the door and window opening, respectively. Figure 4.2 contains a summary of all the details pertaining to the dimensions of the representative dwelling and the instrumentation layout. Note the number in brackets refers to the number of measurement instruments situated within a given equipment tree. The thermocouples distributed along the underside of the roof (i.e. T9, T10 & T11) were placed at 150 mm from ceiling level. The representative

ISD used for all tests conducted is shown in Figure 4.3. Thin-skinned calorimeters were also utilised, as shown, although data from these has been utilised for other research and is not required in this paper.

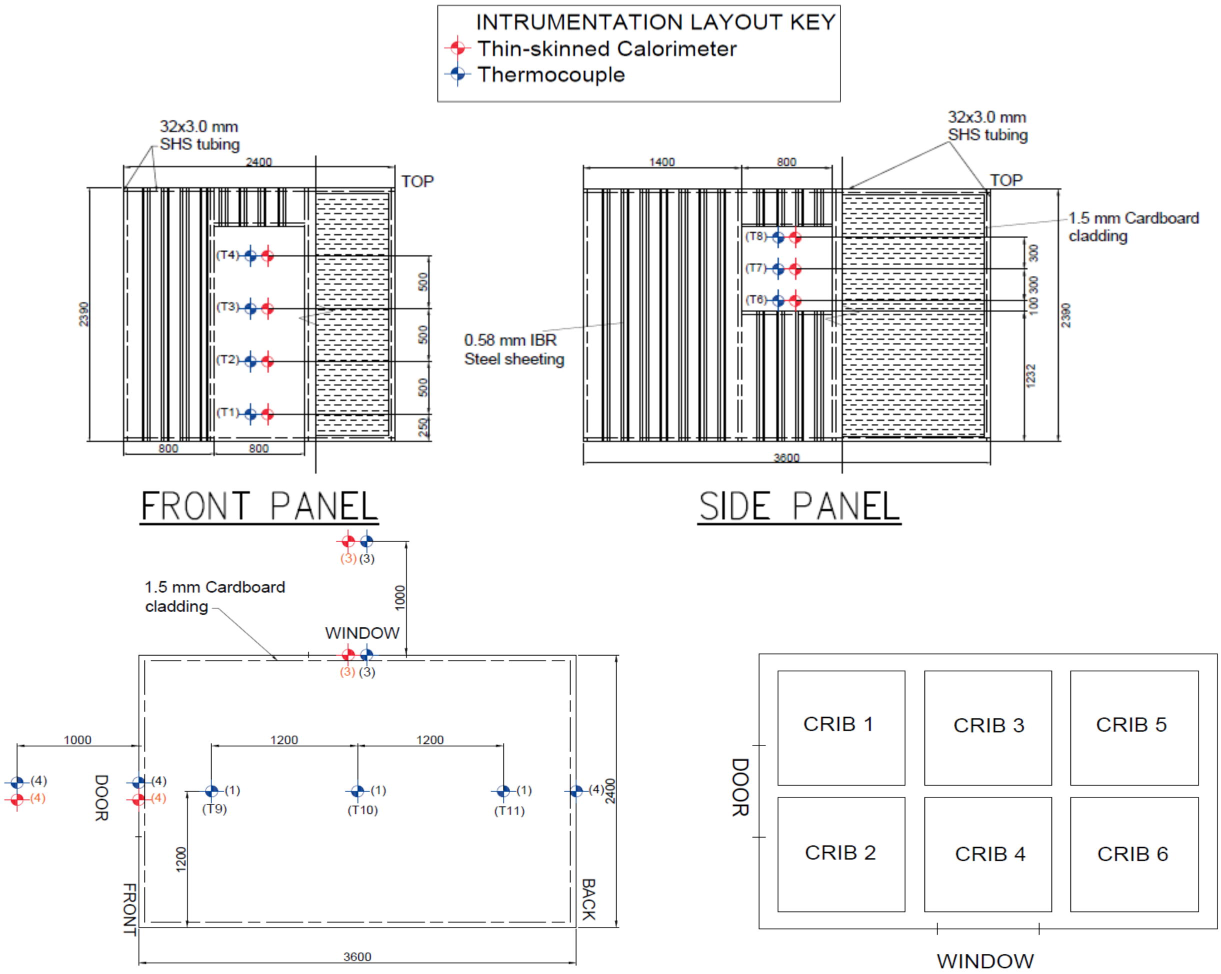

Figure 4.2: Experimental setup indicating dwelling dimensions and instrumentation layout. All dimensions in mm.

Figure 4.3: Representative informal settlement dwelling.

4.3.1. Representative fuel load

The fire load in ISDs varies substantially from one dwelling to another, ranging anywhere from 400-3000 MJ/m² [13][14], depending on the contents of the dwelling as well as the use of construction materials, thereby making it inherently difficult to define a standardized fuel load for these type of dwellings. For this research it was decided to use a fuel load of 410 MJ/m² based on the findings of an independent study which investigated the contents of informal settlement dwellings by means of an inventory survey and found the average fire load density to be 410 MJ/m² with a standard deviation of 140 MJ/m² [13]. The lower limit of the fuel load density is taken, since it resembles the fuel load which can be expected to be found in an 'average' informal settlement dwelling. This excludes any anomalies such as dwellings, which are simultaneously being used as shops which sell highly combustible products such as paraffin. Furthermore, previous research has shown that higher fuel loads in compartments with a similar opening factor simply affect the duration of the fire and not necessarily affect the initial development, since the compartment will become ventilation controlled [15]. Due to the short duration of the fire the total exposed surface area of the fuel is important (i.e. timber fuel source dimensions), and this governs the initial heat release rate, and the difficulty associated with suppressing the fire, meaning a lower fuel load with smaller pieces of timber may be more critical than a higher fuel load with larger pieces. Non-structural pine with a density of 530 kg/m³ and an effective heat of combustion of 16.1 MJ/kg (as measured from a bomb calorimetry test) was selected to obtain an equivalent fuel load of 25 kg/m². The individual timber pieces (50 x 50 x 1000 mm) were aligned in alternating rows which results in the crib configuration depicted in Figure 4.4.

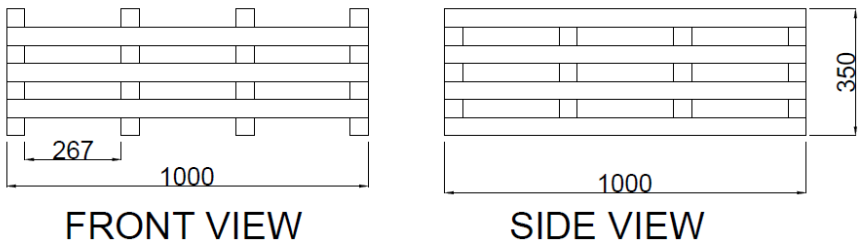

Figure 4.4: Individual crib configuration. All dimensions in mm.

As previously mentioned, occupants of ISDs often line the interior walls as well as the floor of the dwelling with various combustible materials, including cardboard, to provide some relief against the scorching summer days and cold winter nights. Therefore, the interior walls and floor of the representative ISD were lined with 1.5 mm thick corrugated cardboard with a density of 180 kg/m³ and an effective heat of combustion of 16.9 MJ/kg (as measured from a bomb calorimetry test). The combined fuel load density due to the cardboard and timber cribs is approximately 440 MJ/m². The cardboard lining as well as the crib configuration is illustrated in Figure 4.5.

Figure 4.5: Cardboard lining and timber fuel cribs.

The experiments were initiated by igniting a bundle of hessian material which was drenched in paraffin and placed in a steel tray (250 mm in diameter) located on the floor in the centre of *Crib 2.* The hessian bundle would promote the initial fire growth and increase the probability of successful ignition [16].

4.3.2. Experimental Results

After ignition the fire was allowed to develop until post-flashover conditions were achieved and the fire was said to be "fully-developed". Flashover does not occur at a certain point but is rather categorised by a rapid increase in temperature within the compartment with a hot layer temperature of approximately 600 °C or an incident radiative heat flux at floor level of 15 to 20 kW/m² [17]. Since, flashover does not occur at a certain point but rather over a period during which a rapid increase of temperature is measured, it is necessary to determine the point at which the temperature rise begins to slow, thus indicating the transition between the end of the flashover period and the beginning of the fully-developed phase. In order to ensure that the fire is fully-developed and has achieved a relatively steady-state of burning, it was decided to define the point at which the temperature increase begins to slow as the instance at which a ceiling temperature of 850 °C was recorded at one of the three ceiling thermocouples, after which the fire brigade would prepare to intervene.

For the full-scale tests two variations of the bucket brigade technique were tested which was done to investigate the influence of different bucket application rates. The bucket brigade tests consisted of a *continuous application* approach and a *mass application* approach. For the continuous application approach a series of eight 10 litre buckets (filled with 8 litres of water) were continuously circulated between the tap and the burning dwelling (approximately 20 m). The time elapsed between the application of two successive buckets was recorded and varied slightly as a result of the time required to discharge, exchange and refill the buckets but typically ranged between 20 – 30 seconds. In contrast to the continuous application approach, the mass application approach focussed on applying a larger amount of water to the fire at a reduced frequency. For the mass application approach a total of four buckets of water were accumulated before being applied to the fire. Once the water was applied to the fire, the buckets were then transported back towards the water supply point where the process was then repeated. For the test in which a conventional firehose was used, it was decided to use a TFT G-Force selectable flow fog branch with a flow rate of 115 l/min (lpm). From Figure 4.6 it can be seen how the cardboard lining ignites and initiates flashover (top left), which leads to the formation of fully-developed fire (top right).

Figure 4.6: Full-scale experimental testing. Flashover with flames emerging from door opening (top left), full-developed fire (top right), intervention using firefighting hose (bottom left), intervention using bucket brigade (bottom right)

The average roof temperatures associated with the bucket brigade tests, water jet test as well as the average roof temperature of the burnout test are depicted in Figure 4.7, indicating the average temperature response at roof level, following the initiation of the suppression phase. Note that the water was applied onto the cribs meaning that there was a delay in the cooling of the gas temperature at the roof, as can be seen in Figure 4.7. From the time-temperature response it can be noted that all three interventions are successful at suppressing the fire, however, the bucket brigade technique which focusses on applying a greater amount of water at a reduced frequency results in a more rapid initial temperature reduction following the application of water.

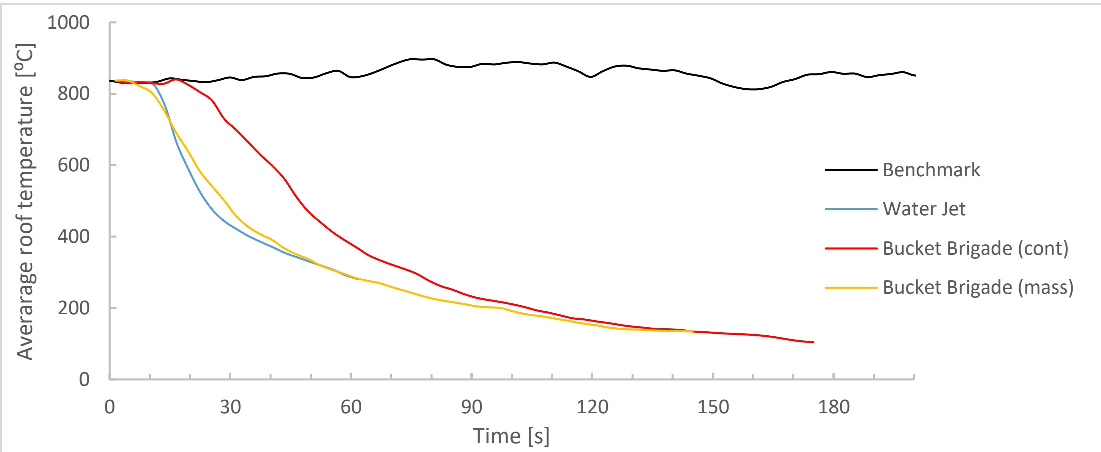

Figure 4.7: Average roof temperature response of selected interventions following the initiation of the suppression phase.

Table 4.2 provides a summary of the most important parameters pertaining to the experimental data measured during the bucket brigade tests as well as during the water jet test.

Table 4.2: Summary of most important experimental results

	Bucket Brigade (mass)	Bucket Brigade (cont.)	Water Jet
Max. Temperature	922 ^oC	925 ^oC	869 ^oC
Max. avg. Temperature	891 ^oC	890 ^oC	833 ^oC
Intervention duration	2 min 24 sec	2 min 58 sec	1 min 0 sec
Temperature decrease	718 ^oC	737 ^oC	556 ^oC
Water used	64 litres water	72 litres water	100 litres water

The work in the succeeding sections will focus explicitly on the bucket brigade technique utilising the continuous approach, since the continuous approach is generally adopted by residents in the event of a real-life informal settlement fire. Further work is required to investigate the effects of various discharge rates as well as travelling distances between standpipes and the affected ISD on the suppression duration when adopting the mass application approach.

4.4. Development and analysis of the FDS base model

4.4.1. Computational domain and cell size

The first step in developing an FDS model which can be used to analyse the effects of varying application and discharge rates during the suppression phase is to establish an appropriate size for the computational domain and cell size. The dimensions of the dwelling used in the experiments were 2.4 x 3.6 x 2.4 m (width x breadth x height). Therefore, a computational domain size of 4.4 x 5.6 x 3.0 m was selected. The maximum cell size is limited to 0.1D* for plume fires where D* is the characteristic fire diameter [m] and can be determined according to equation (4.1) [18].

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty T_\infty c_p \sqrt{g}}\right)^{2/5} \tag{4.1}$$

where $\dot{Q}$ is the heat release rate (HRR) of the fire [kW], ρ_∞ is the ambient air density [kg/m³], T_∞ is the ambient temperature [K], c_p is the specific heat [kJ/(kg·K)] and g is the gravitational acceleration [m/s²]. For this investigation a peak HRR of 3850 kW was obtained which yields a characteristic fire diameter of 1.50 m (the calculation of the limiting HRR value is discussed in the following section). Therefore, the cell size should not exceed 150 mm. For the development of the FDS model a cell size of 100x100x100 mm was chosen, thereby yielding a total of 73 920 cells across the computational domain. A substantial amount of work within the greater fire community has been aimed at analysing the effect of the cell size for plume fires. The cell size of 100 mm is less than 0.1D* and therefore the cell size should have a negligent impact on the gas temperature measured within the enclosure. This is backed up by research conducted by other authors, which found that refining the cell size for a 3 x 3 x 2.3 m enclosure with an initial cell size of 100 mm by a factor of 2 has a negligible effect on the fire development, while increasing the computational effort required substantially [19].

It is necessary for obstructions within the model to coincide with the mesh of the computational domain and therefore it was required to slightly modify the dimensions of the window opening. As a result, the window opening was placed at 1.20 m above the ground level (1.23 m in experiment).

4.4.2. Heat release rate

Due to the size of the experiment, the HRR could not be measured over the course of the full-scale test. The development of a model which accurately captures the pyrolysis process is challenging due to the intricacies pertaining to the pyrolytic decomposition of the combustible material, which in turn consists of a series of complex sub-reactions on a microscopic scale. It is therefore often beneficial to adopt a simplified pyrolysis model in which a prescribed Heat Release Rate per Unit Area (HRRPUA) is assigned to a surface, which essentially functions as a burner within a compartment. Previous research has shown that there is a good correlation between the detailed analysis and simplified analysis approach [14][19]. Furthermore, when considering the massive variation in informal settlements, in terms of both construction materials and home contents, approximate answers which can be parametrically studied are of greater use than precise solutions based on unknown inputs.

The mass burning rate, and therefore the HRR of timber cribs has been extensively studied by other authors [20] and can be determined according to equation (4.2).

$$\dot{Q} = \dot{m}\Delta H_{eff} \tag{4.2}$$

Where $\dot{m}$ is the mass loss rate [kg/s] and $\Delta H_{eff} = 16.1\ MJ/kg$ is the effective heat of combustion, as measured from a bomb calorimetry test. For timber cribs the mass loss rate is limited by one of three factors, namely (a) flow rate of air and combustion products through the air gaps in the crib, (b) the exposed surface area of the fuel, and (c) amount of oxygen entering the compartment. The equations describing the mass loss rate limits for the three cases are listed below [20]:

- Porosity controlled: $\dot{m} = 4.4\ x\ 10^{-4}\left(\frac{s}{h_c}\right)\left(\frac{m_0}{D}\right)$ (4.3)

Where D is the stick thickness (0.05 m), s is the clear spacing between adjacent sticks (0.27 m), h_c is the crib height (0.35 m) and m_0 is the initial crib mass (225.12 kg).

- Surface controlled: $\dot{m} = \frac{4}{D}\ m_0 v_p\left(1 - \frac{2v_p t}{D}\right)$ (4.4)

Where v_p = 2.2 x $10^{-6}D^{-0.6}$ for timber [20].

- Ventilation controlled: $\dot{m} = 0.12A_v\sqrt{h_v}$ (4.5)

Where A_v is the ventilation opening area (2.24 m²) and h_v the ventilation opening height (1.66 m). FDS determines whether combustion can occur based on the temperature within a given cell as well as ensuring that there is sufficient oxygen and fuel available for the combustion reaction [18].

Based on the equations (4.3) – (4.5) it was found that the mass loss rate of the fire is surface-controlled thereby yielding a peak HRR of 3.85 MW. The timber cribs were modelled as six individual 0.9 x 0.9 m burners situated within the dwelling, thus resulting in a peak HRRPUA of 792.02 kW/m² i.e. a peak HRR of 641 kW per burner. The burners were set to activate once the temperature recorded at the top of the crib reached 350 ºC i.e. the ignition temperature of the timber.

The results from a Fire Propagation Apparatus test are illustrated in Figure 4.8 and were used to model the HRRPUA of the cardboard lining. The Fire Propagation Apparatus test was conducted at the University of Edinburgh during which a heat flux of 50 kW/m² was used [19].

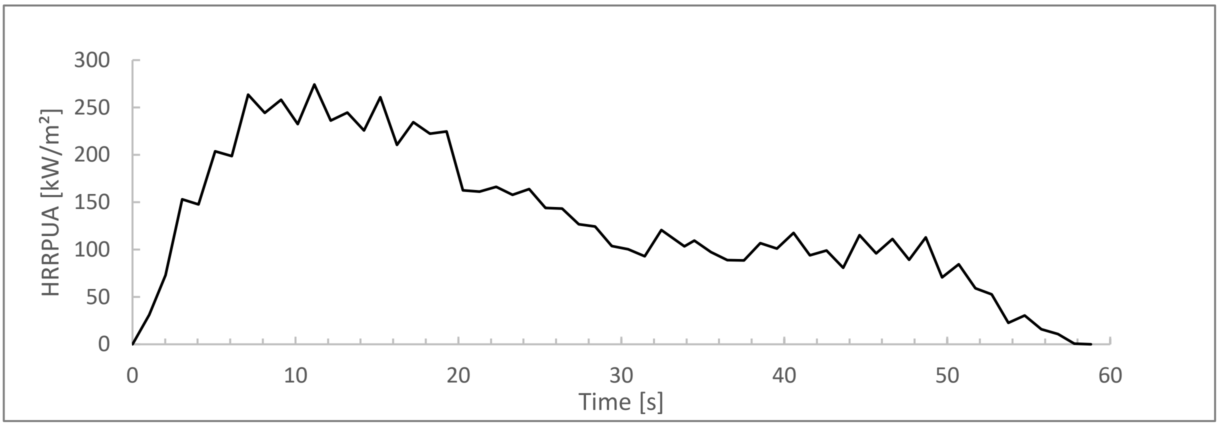

Figure 4.8: Cardboard HRRPUA from Fire Propagation Apparatus test

4.4.3. Materials and thermal material properties

In order to accurately describe the heat transfer in the system and simulate the fire development it is necessary to create different materials within FDS and assign the necessary thermal material properties to the respective materials. For this model it was required to create two materials, namely the steel required for the sheeting and the corrugated cardboard used as the lining material. The material properties for the corrugated cardboard had to be adjusted, since the thickness of the cardboard is less than the cell size of 100 mm used throughout the computational domain. Each obstruction within the model is required to be at least one cell size thick in order to guarantee full functionality [18]. The cardboard lining thus had to be modelled as 100 mm thick and the density of the material had to be adjusted to account for the volumetric change of the obstruction in the model. Table 4.3 depicts various material properties associated with the steel and corrugated cardboard used in the FDS model. The information pertaining to the material properties was sourced from [21-27]. The values depicted in **Bold** are the values used for the input parameters in the model. Cicione et. al [14][19] have done extensive work based on similar experiments to validate the parameters used, and the methodology applied in this work.

Table 4.3: Material properties used as input parameters for FDS model.

Material Property	***Steel***	***Cardboard***
Density, ρ [kg/m³]	7850 [21]	180 (2.7 used in model)*
Specific Heat, c [kJ/(kg·K)]	0.6 [21]	1.52 - **2.7** [22] [23]
Conductivity, κ [W/(m·K)]	45 [21]	0.064 - **0.42** [22] [24-26]
Emissivity, ε	0.42 [21]	0.7 - **0.9** [25] [26] [27]
Ignition temperature [°C]	-	263 – **323** [27]

**Adjusted to account for volumetric change of obstruction in model*

Details regarding the obstruction properties for the steel sheeting and the cardboard lining contained within the dwelling are listed in Table 4.4.

Table 4.4: FDS obstruction properties

	Steel sheeting	**Cardboard lining**
Obstruction thickness (actual)	*0.58 mm*	*1.5 mm*
Obstruction thickness (model)	100 mm	100 mm
Surface thickness (model)	0.29 mm	50 mm
Backing condition (model)	Exposed	Air Gap

The final aspect which needs to be accounted for in the base model is the effect of the leakages experienced at the wall-roof intersections of the sheeting, which occurs as a result of the sheeting profile. Since the leakage area is substantially smaller than the mesh resolution it is not possible to simply leave a one-cell gap at the top of the wall sheeting as this would allow too much heat to escape through the gap. The leakages were therefore modelled by utilizing the HVAC function in FDS with a specified leakage area of 0.041 m^2 and a flow loss of 0.1. The resulting base model is depicted in Figure 4.9.

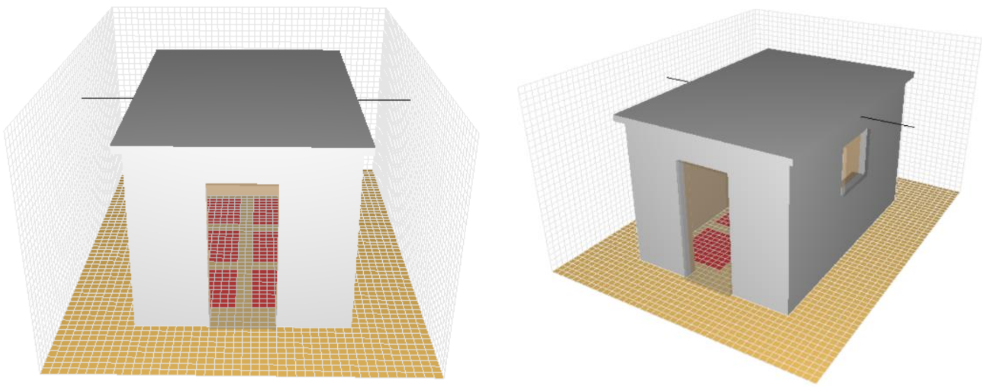

Figure 4.9: Various views of FDS model used for suppression simulations.

4.4.4. Comparison of full-scale benchmark test and FDS model results

The resulting average roof temperature for the burnout test is depicted in the time-temperature curve in Figure 4.10. As previously mentioned, the purpose of the burnout test was to establish the nature of the fire development which can then be used as a benchmark to determine the suppression ability of the tested interventions. The initial fire growth and flashover period are captured fairly accurately in the FDS model. The FDS model accurately captures the burn out of the cardboard lining at approximately 150 seconds although the peak temperature is over-estimated by 14%. This most likely occurs since the spread rate over the surface of the cardboard is slightly greater than that observed during experimental testing. In the model, the fire spread rate across the cardboard lining is greater and as a result more heat is released, since a larger amount of cardboard is burning at a given time. This behaviour has previously been documented by other authors [19]. However, in general a good correlation between the FDS model and the full-scale experiment can be observed once the cardboard lining has burnt away, and the timber cribs have successfully been ignited throughout the dwelling.

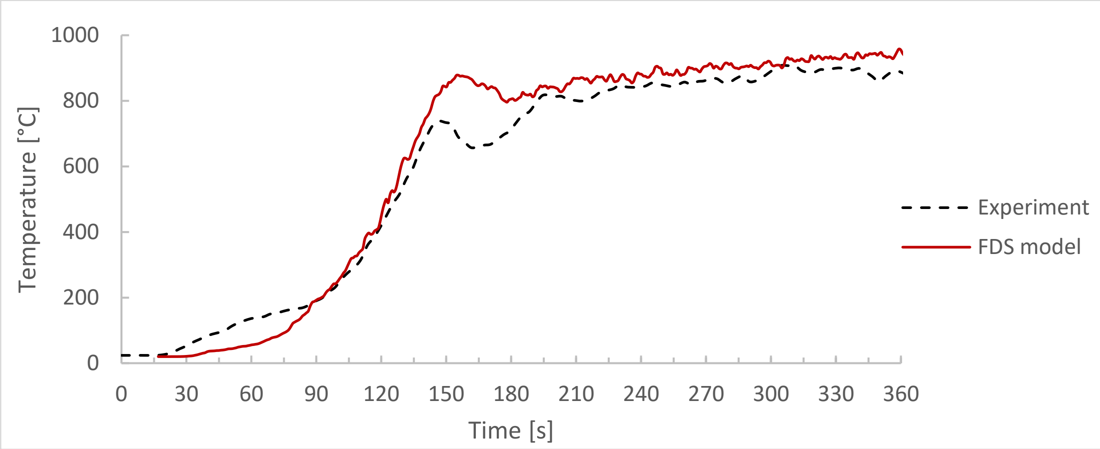

Figure 4.10: Comparison of average measured roof gas temperatures from experiment vs FDS model during fire development stage.

4.5. Development and analysis of the suppression model

When adopting the burner approach in FDS to simulate a fire, suppression by water is controlled by means of an *extinguishing coefficient*, which governs the suppression response following the introduction of water. The extinguishing coefficient is responsible for the exponential decay of the burning rate associated with the fuel (and hence of the HRR), once water is introduced into the model. The reduction of the burning rate after the application of the water is expressed in equations (4.6) and (4.7) [18].

$$\dot{m}_f''(t) = \dot{m}_{f,0}''(t)e^{-\int k(t)dt} \tag{4.6}$$

where $\dot{m}_{f,0}''$ $[\frac{kg}{sm^2}]$ is the original user-defined mass loss rate per unit area prior to the introduction of water into the computational domain, while $\dot{m}_f''$ is the reduced mass loss rate per unit area at a given time following the initiation of the suppression phase. The parameter $k(t)$ is a function of the extinguishing coefficient and the water mass per area, m_w'' $[\frac{kg}{m^2}]$, which dictates the reduction of the mass loss rate [18]:

$$k(t) = E_{COEFFICIENT}\, m_w''(t)\ \left[\frac{1}{s}\right] \tag{4.7}$$

The extinguishing coefficient is an empirical parameter and needs to be determined experimentally. The results from the full-scale experimental test were used to obtain an appropriate value for the extinguishing coefficient, thereby serving as a calibration model for the simulations in subsequent sections. Figure 4.11 illustrates and compares the average roof gas temperature measured during full-scale experimental testing with the average roof temperature measured within the dwelling for various extinguishing coefficients, following the introduction of the first bucket of water at time t=0 sec. A value of 0.20 for the extinguishing coefficient provides a good correlation between the results obtained from the full-scale experiment and the FDS model, and therefore a value of 0.20 will be used for the remaining simulations.

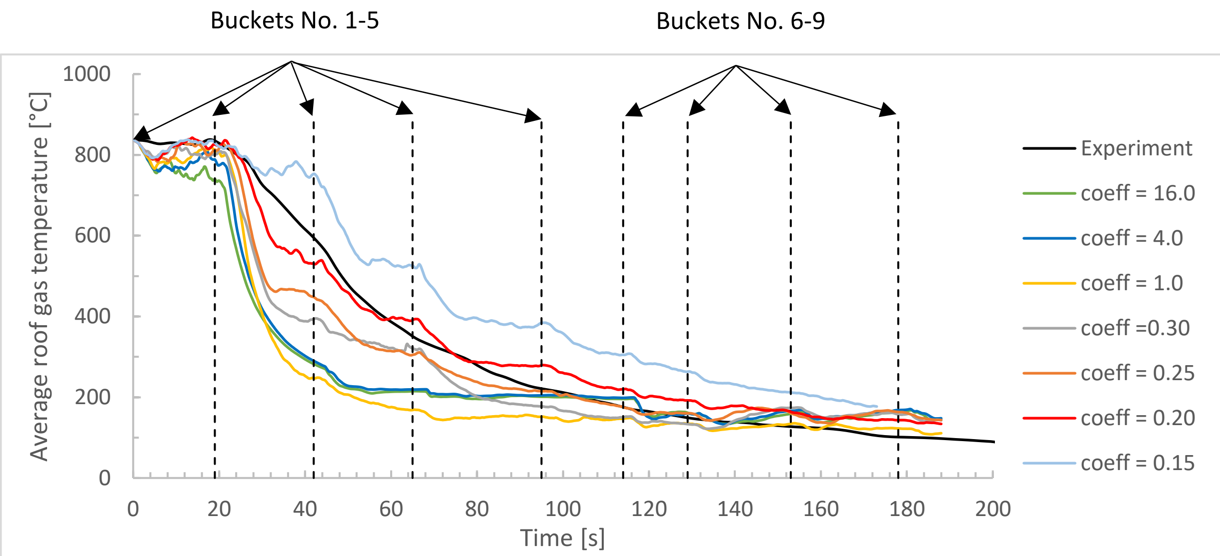

Figure 4.11: Influence of the extinguishing coefficient on the suppression duration for a discharge rate of 60 lpm at 20 m travelling distance (Vertical lines indicate instance at which a bucket of water is applied to the fire).

4.5.1. Sensitivity study of the extinguishing coefficient

The response of the fire following the initiation of the suppression attempt is governed by the extinguishing coefficient and the local water mass per area and therefore it was decided to conduct a sensitivity study to determine the model's sensitivity towards the extinguishing coefficient. For the sensitivity study it was decided to investigate the influence of selecting an extinguishing coefficient of 0.25 and 0.15 compared to the extinguishing coefficient of 0.20 for a travelling distance of 20 m and standpipe discharge rates of 40, 23 and 10 lpm, respectively. The response of the average roof temperature for the respective extinguishing coefficients and standpipe discharge rates are illustrated in Figure 4.12 for a travelling distance of 20 m. It can be seen that the selection of the extinguishing coefficient primarily has an effect on the average roof temperature response for the first 2 - 3 buckets of water after which the individual time-temperature curves begin to converge. It should be noted, as the discharge rate decreases, the temperature response for an extinguishing coefficient of 0.15 begins to deviate from the corresponding time-temperature responses for extinguishing coefficients of 0.20 and 0.25, respectively. This occurs due to the exponential function, which governs the suppression response. As the extinguishing coefficient approaches a value of zero, the resulting change in burning rate following the introduction of water into the model becomes insignificant, thus limiting the suppression ability, regardless of the discharge rate.'

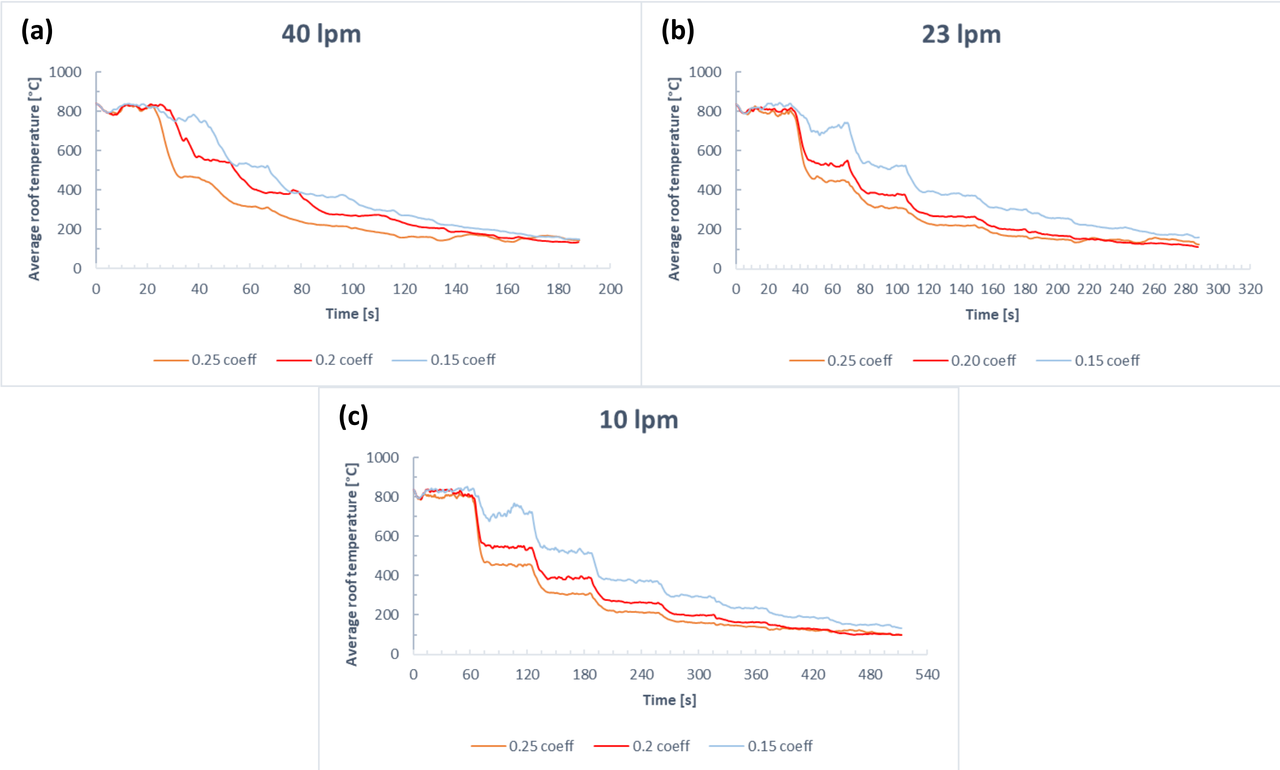

Figure 4.12: Sensitivity study for extinguishing coefficients of 0.15, 0.20 and 0.25 for a travelling distance of 20 m and standpipe discharge rates of (a) 40 lpm, (b) 23 lpm and (c) 10 lpm.

4.5.2. Mesh sensitivity analysis

A mesh sensitivity study was performed to determine the model's sensitivity towards the cell size. The sensitivity of the model was established by refining the initial cell size of 100 mm to 50 mm, thus increasing the number of cells contained within the computational domain from 73920 to 591 360. The average roof temperature response following the initiation of the suppression phase is depicted in Figure 4.13. From Figure 4.13 it can be seen that only minor changes will occur as a direct result of the mesh refinement, however, the suppression response converges with that of the 100 mm mesh and the time to suppression is virtually unaffected by the mesh size and therefore it can be established that refinement of the mesh has a negligible effect on the gas temperature measured at roof level. A further point to consider is the computational effort required to conduct the simulation. A mesh reduction with a factor of 2 results in an increase in simulation time of more than 10 times on the computer system utilized, thus making the model computationally inefficient.

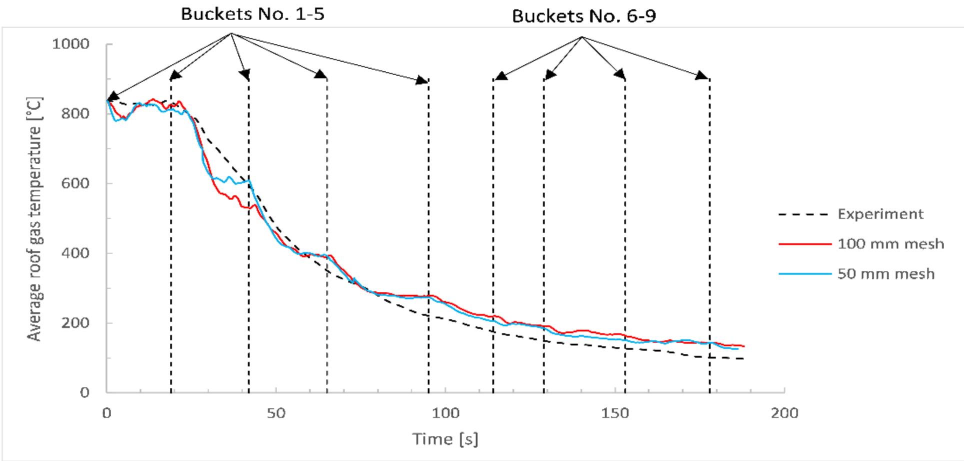

Figure 4.13: Mesh sensitivity analysis investigating the effect of the cell size on the average roof temperature in comparison to experimental results.

4.5.3. Influence of standpipe discharge rates and distance from affected dwelling

Due to the absence of basic infrastructure within informal settlement communities, water is often provided by means of communal standpipes within these areas. In South Africa, the minimum water supply per capita as well as the maximum distance from a dwelling to the nearest standpipe are outlined in the national legislation [28]. The provision of a single standpipe with a minimum discharge rate of 10 lpm is prescribed per 25-50 dwellings. Table 4.5 provides various discharge rates at different pressure heads for taps commonly used in informal settlements in South Africa. Note that the high discharge rates obtained for a pressure head of 60m are typically reduced to 40 l/min due to restrictions associated with the pipework [28].

Table 4.5: Typical discharge rates for common taps used in informal settlements in South Africa (assumed efficiency rate of 80%) [28].

Tap Diameter	Discharge rate		
	5m head	10m head	60m head
15 mm	16 l/min	23 l/min	54 l/min
20 mm	22 l/min	31 l/min	70 l/min

The following section will focus on how different discharge rates and travelling distances affect the suppression ability and duration of bucket brigades in post-flashover ISD fires. The same application sequence is adopted for each simulation i.e. the buckets of water are applied in the same configuration adopted in the full-scale experiment and calibration model. The time-temperature responses for the average measured roof gas temperatures following the initiation of the suppression stage for various discharge rates are illustrated in Figure 4.14 for a travelling distance of 20m, 50m, 100m and 200m, respectively. Note, the time required to travel from the standpipe to the dwelling was determined based on a walking speed of 5 km/h (1.39 m/s) as recommended for visibility levels of greater than 3 m [29]. In reality, the transfer of water across larger distances will lead to higher losses, due to spillage.

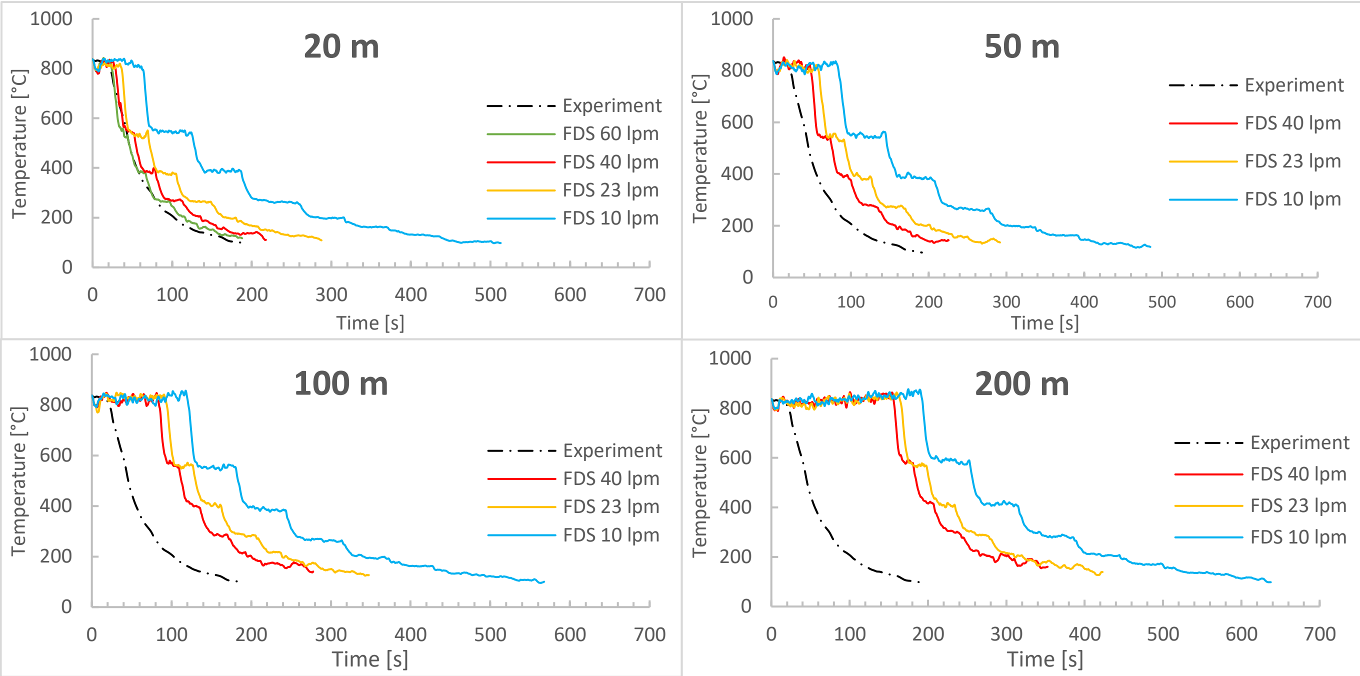

Figure 4.14: Extinguishing response for various travelling distances and discharge rates.

With reference to Figure 4.14 it can be observed that the distance between the standpipe and the affected burning ISD has a considerable influence on the extinguishing duration. The most noteworthy difference between the various travelling distances and standpipe discharge rates analysed is the effect on the additional time required for the application of the first bucket of water to the fire, which ranged between 4 – 169 seconds depending on the distance between the ISD and the standpipe as well as the discharge rate at the standpipe. Table 4.6 and Table 4.7 provide a summary regarding the additional time required for the application of each individual bucket of water for the various analysed discharge rates and walking distances compared to the time of application measured during the experiment, which were captured based upon video recordings. Table 4.6 and Table 4.7 exemplify the significance of the travelling distance and discharge rate on the bucket application times. This is an issue of concern, especially in informal settlement communities, where dwellings are predominantly constructed from combustible materials, since the fire will spread to adjacent dwellings before the first bucket of water is applied to the dwelling of fire origin.

Table 4.6: Effect of standpipe discharge rates on the water bucket application times for a travelling distance of 20m (Number in brackets indicating additional time required for application of bucket, expressed as a percentage). The 60 lpm column represents the experimental data and is used as a benchmark against which results of other flow rates are compared.)

	20 m travelling distance						
	Test 60 lpm	FDS 40 lpm		FDS 23 lpm		FDS 10 lpm	
	Time of application (sec)	Time of application (sec)		Time of application (sec)		Time of application (sec)	
Bucket 1	0	4	(-)	13	(-)	40	(-)
Bucket 2	19	27	(-42%)	45	(-137%)	99	(-421%)
Bucket 3	42	54	(-29%)	81	(-93%)	162	(-286%)
Bucket 4	65	81	(-25%)	117	(-80%)	225	(-246%)
Bucket 5	95	115	(-21%)	160	(-68%)	295	(-211%)
Bucket 6	114	138	(-21%)	191	(-68%)	354	(-211%)
Bucket 7	129	157	(-22%)	219	(-70%)	409	(-217%)
Bucket 8	153	185	(-21%)	256	(-67%)	473	(-209%)
Bucket 9	178	214	(-20%)	294	(-65%)	538	(-202%)

Table 4.7: Effect of standpipe discharge rates on the water bucket application times for a travelling distance of 200m (Number in brackets indicating additional time required for application of bucket, expressed as a percentage). The 60 lpm column represents the experimental data and is used as a benchmark against which results of other flow rates are compared.)

	200 m travelling distance						
	Test 60 lpm	FDS 40 lpm		FDS 23 lpm		FDS 10 lpm	
	Time of application (sec)	Time of application (sec)		Time of application (sec)		Time of application (sec)	
Bucket 1	0	133	(-)	142	(-)	169	(-)
Bucket 2	19	156	(-721%)	173	(-811%)	228	(-1100%)
Bucket 3	42	183	(-336%)	209	(-398%)	291	(-593%)
Bucket 4	65	210	(-223%)	245	(-277%)	354	(-445%)
Bucket 5	95	244	(-157%)	288	(-203%)	424	(-346%)
Bucket 6	114	267	(-134%)	320	(-181%)	483	(-324%)
Bucket 7	129	286	(-122%)	348	(-170%)	538	(-317%)
Bucket 8	153	314	(-105%)	385	(-152%)	602	(-293%)
Bucket 9	178	343	(-93%)	423	(-138%)	667	(-275%)

In addition to the effect of the distance between the affected dwelling and the nearest standpipe, it can also be observed that the discharge rate of the standpipe has a substantial effect on the suppression duration. The time required to extinguish the fire within the dwelling increases significantly as the water discharge rate at the standpipe is reduced. With regards to Figure 4.14, as well as Table 4.6 and Table 4.7 it can be observed that the effect of the discharge rate on the suppression duration is not substantial for a for a standpipe with a discharge rate of 23 lpm and 40 lpm, respectively, since the difference in the time required to fill a given bucket with 8 litres of water is approximately 9 seconds. However, the same does not apply for a discharge rate of 10 lpm, since the time required to fill a single bucket with 8 litres of water increases significantly (approximately 36s longer compared to a discharge rate of 40 lpm). This in turn has a substantial effect on the extinguishing duration even for a short travelling distance of 20 m. Therefore, a discharge rate in the order of 23 lpm would, as provided by a 15 mm diameter tap with a pressure head of 10 m, would, in many cases, be sufficient to suppress a fire, providing that a single home is burning, and all water is transferred to it. A supply rate of 10 lpm, as required by legislation, would result in suppression occurring too slowly, meaning that fire would rapidly spread to adjacent dwellings, following which community suppression efforts would probably no longer be feasible.

4.5.4. Influence of fire load

As discussed previously, one of the biggest uncertainties associated with informal settlement fires is the variation in terms of the fuel load contained within the dwellings. Reports from literature have identified that the fuel load ranges anywhere between 400 – 3000 MJ/m², depending on the contents of the dwelling. For this investigation the lower limit of 410 MJ/m² was used. This section investigates the influence of the fuel load on the suppression performance if the fuel load is increased to 780 MJ/m², as prescribed by EN 1991-1-2 for formal dwellings [21]. A fuel load of 780 MJ/ m² yields a maximum HRR of 5.77 MW based on equations (4.2) - (4.5). The same configuration for the application of the water is maintained as in the previous suppression models.

The resulting time-temperature responses for a travelling distance of 20 m and 200 m are depicted in Figure 4.15, which illustrates the difference in terms of the suppression performance for a fuel load of 410 MJ/m² and 780 MJ/m², respectively.

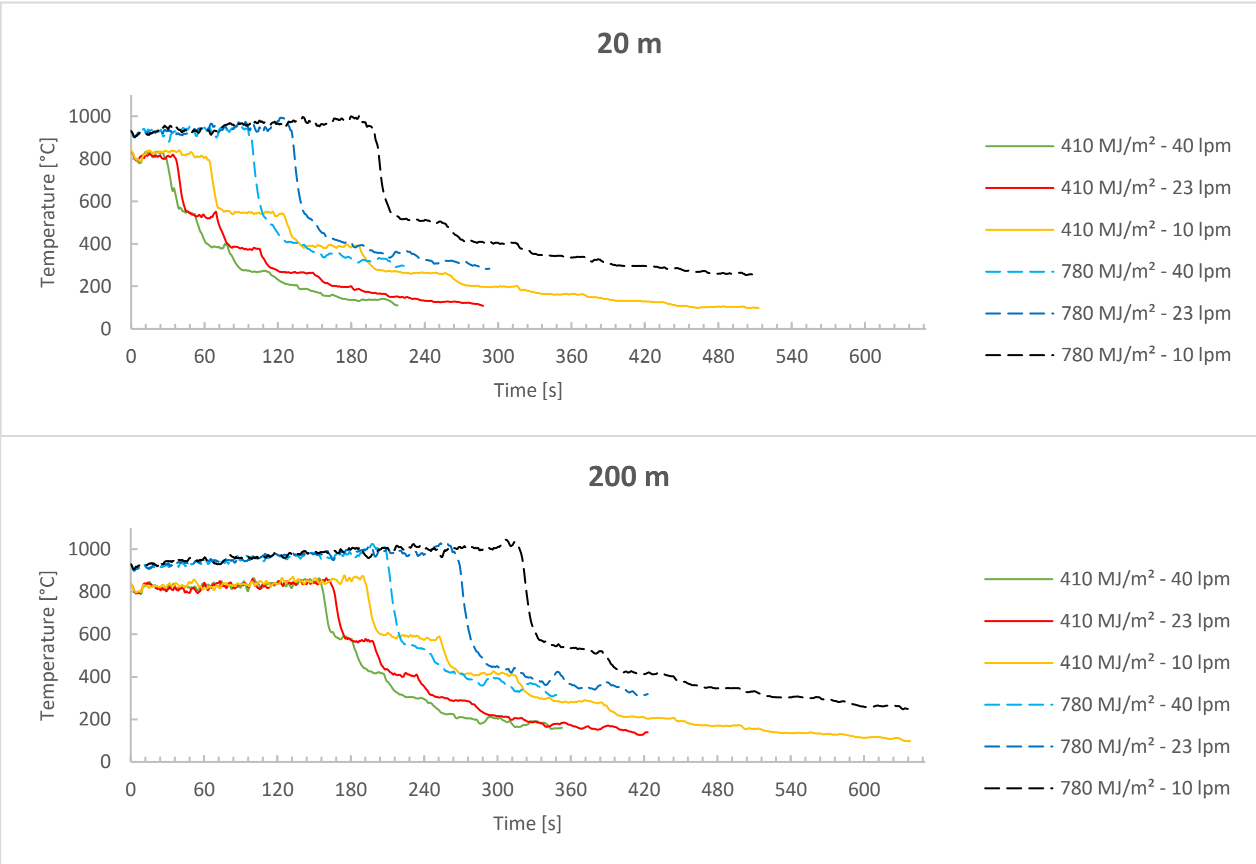

Figure 4.15: Influence of fuel load on suppression performance.

With reference to Figure 4.15, the most noticeable difference in terms of the temperature response for the two different fuel load cases, is the amount of water required to initiate the temperature reduction within the enclosure. When compared with the 410 MJ/m² fuel load test, an additional delay of approximately 130 seconds was recorded between the time at which the first bucket of water was applied to the fire until a substantial decline of the roof temperatures was recorded. A delay of 130 seconds corresponds to a time during which 4 buckets of water are applied to the fire at a discharge rate of 40 lpm. The suppression ability of a single bucket of water is reduced significantly for a fuel load of 780 MJ/m², since the issue of re-ignition of the timber cribs is introduced. A single bucket of water cannot effectively put out an entire burning timber crib and therefore the fire maintains its intensity until sufficient water has been introduced into the dwelling to absorb enough heat which results in the sudden decline in the measured average roof temperature. In addition to the delay associated with the rapid temperature reduction, it should be noted that the measured roof temperature after the application of the final bucket of water is 154 – 186 °C higher for a fuel load of 780 MJ/m² when compared with the models with a prescribed fuel load of 410 MJ/m². Table 4.8 provides a summary of the average roof temperature measured shortly after the application of the 4th bucket of water.

Table 4.8: Influence of fuel load and travelling distance on the average roof temperature following the application of the 4th bucket of water.

Travelling Distance	410 MJ/m²				780 MJ/m²		
	Experiment 60 lpm	40 lpm	23 lpm	10 lpm	40 lpm	23 lpm	10 lpm
20 m	339 °C	305 °C	329 °C	341 °C	955 °C	938 °C	972 °C
50 m	-	341 °C	342 °C	341 °C	-	-	-
100 m	-	351 °C	352 °C	341 °C	-	-	-
200 m	-	377 °C	373 °C	362 °C	972 °C	980 °C	984 °C

From Table 4.8 it becomes evident that the suppression ability of the bucket brigade technique becomes limited as the fuel load is increased. Although the fire could eventually be extinguished, the additional time required to suppress the fire is certainly substantial and will, in most instances, result in fire spread, even with the maximum prescribed standpipe discharge rate of 40 lpm. The average roof temperatures after the application of the fourth bucket of water were approximately 600 – 650 °C higher for a fuel load of 780 MJ/m². The results obtained for the models utilizing a fuel load of 780 MJ/m² requires further research and calibration, since the extinguishing coefficient used for the suppression modelling is an empirical parameter obtained from full-scale testing and is therefore not ideal for predicting the thermal response after the introduction of the water into the computational domain. Furthermore, from the onset it was mentioned that civilian firefighting is not ideal, and is done out of necessity rather than preference, it should be noted that civilians might not be able to get close enough to the dwelling in the event of a fire when the associated fuel load is very high, due to the elevated temperatures and radiation experienced at the enclosure openings. Due to a lack of protective gear, civilians would therefore have to apply the water from a greater distance, thus reducing the accuracy of the discharge, thereby resulting in a less effective suppression attempt.

4.6. Conclusion

This investigation focussed on developing suppression models in FDS to model the suppression phase of post-flashover ISD fires when utilizing the bucket brigade technique. The models relating to the fire development as well as the suppression response presented good correlation with the results obtained from previous full-scale testing.

It should be acknowledged that the conditions for the full-scale experiment and therefore the input parameters for the FDS models are optimal, since only a single ISD was regarded and the effects of fire spread, thermal feedback and reduced accessibility in the event of a fire were omitted. Furthermore, it was assumed that all standpipes are fully operational and accessible to residents which is not necessarily the case in informal settlements, since the standpipes are often faulty or not accessible. It was documented that residents sometimes construct their homes over standpipes to claim the standpipe for personal use [30]. The effectiveness of the bucket brigade technique is inversely proportional to the number of dwellings affected by the fire. Multiple burning dwellings would see a wider distribution of buckets, which will in turn increase the circulation time of the buckets. Furthermore, it could occur that the accessibility to the initial dwelling of interest is restricted as a result of fire spread to neighbouring dwellings.

It should be acknowledged that a fully operational fire brigade remains the most effective way of extinguishing post-flashover fires, since firefighters are trained and appropriately equipped to analyse and predict the behaviour and combat such fires. However, it is shown that bucket brigades can be effective at extinguishing or preventing the spread of fires, even for post-flashover fires, but often a sufficiently reliable water supply cannot be guaranteed. As a simple recommendation stemming from this work, residents in ISDs should always have a bucket filled with water in their dwelling at all times, thereby potentially extinguishing a fire before it becomes fully developed or alternatively reducing the time required for the application of the first bucket of water to the affected dwelling in the event of a fire. Each settlement would need to be treated on a case-by-case basis to understand what infrastructure is available, and fire response strategies for communities developed accordingly.

4.7. Acknowledgements

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Chapter 5: Conclusion

5.1. Overview

The work addressed in this research investigation has provided a greater understanding of (a) the effectiveness of various suppression products and systems for post-flashover informal settlement fires, and (b) the use of numerical models to predict the response of post-flashover informal settlement dwelling fires following the initiation of the suppression phase. Figure 5.1 illustrates the structure of this thesis along with potential areas of interest for future work. Chapter 1 introduced the need for the work and provides an outline of the problem statement, along with the project goal and individual objectives. Chapter 2 comprises of an extensive literature study which includes a review of the most important literature studied to obtain a core understanding required for the remainder of the work. The most important concepts addressed included (a) fire dynamics in ISDs, (b) science of compartment fires, (c) fire protection strategies and (d) an overview of numerical modelling of enclosure fires.

Chapter 3 presented a novel full-scale testing methodology which can be adopted to evaluate the suppression ability of various existing active fire protection strategies for post-flashover ISD fires. Chapter 3 commenced by introducing the representative ISD used for the full-scale testing along with other factors associated with the execution of the full-scale experimental procedure. The time-temperature data from the full-scale experiments is summarised and the results are analysed and discussed.

Lastly, Chapter 4 focussed on the numerical modelling of water as a suppression medium for post-flashover ISD fires. The effect of various discharge rates from communal standpipes as well as the effect of the distance from the standpipe to the affected dwelling on the suppression time is analysed.

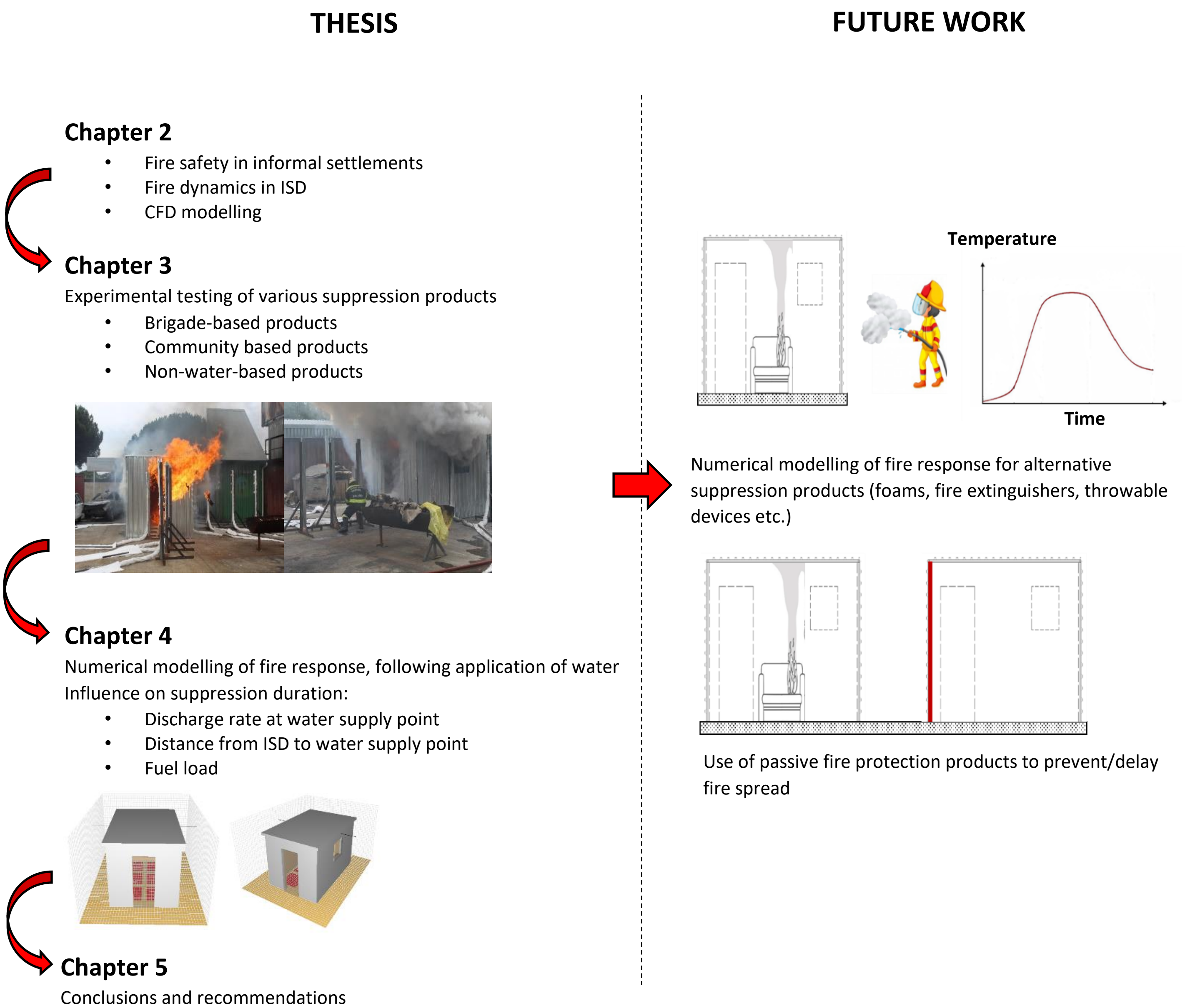

Figure 5.1: Research investigation outline including potential future work

5.2. Summary of findings

5.2.1. Full-scale experimental results

The work discussed in this thesis forms part of a larger research project and focussed on active fire protection systems in post-flashover informal settlement fires. A variety of brigade-based, community-based as well as non-water-based products were tested. From the full-scale experiments, it was shown that the water-based products outperformed the non-water-based counterparts, with the exception of the DCP fire extinguisher which performed very well. (Note: This applies to the experimental setup utilised, and will not apply to all fires, such as oil fires, as discussed in Section 3.3.3). This can be attributed due to the water absorbing the heat within the dwelling, thereby lowering the temperature and preventing re-ignition from occurring. In contrast, the throwable products (fire extinguishing ball, throwable fire extinguishing unit) were unable to suppress the fire and are therefore not suitable for post-flashover fires. The various tested fire protection products were evaluated based on their effectiveness, efficiency and appropriateness. The tested interventions were evaluated based upon a AHP model and the resulting ranking is illustrated in Table 5.1.

Table 5.1: Ranking of interventions showing fire brigade interventions in red and community-based in blue.

Intervention	***Normalized Rating***	***Rank***
CAFS	1.000	1
NAFS	0.936	2
Water Jet	0.816	3
Bucket Brigade (mass)	0.759	4
Bucket Brigade (cont.)	0.720	5
DCP	0.536	6
~~Fireball *~~	~~0.204~~	~~7~~
~~Throwable *~~	~~0.177~~	~~8~~

*Interventions did not succeed in suppressing the fire and should therefore not be considered in the ranking of this investigation as suitable for large-scale implementation

Active fire protection strategies such as NAFS and CAFS, which have a high rating are not necessarily always viable options, since the use of NAFS and CAFS units is typically limited to municipalities with larger annual budgets or they are shared among several municipalities due to the high capital costs associated with the units. Furthermore, the CAFS unit utilised was potentially too large for informal settlement fires, and a smaller unit may be more suitable.

5.2.2. Numerical modelling

The second portion of this work focussed on developing a series of simplified FDS models pertaining to the temperature response within the enclosure, following the initiation of the suppression phase when utilising the bucket brigade technique for post-flashover ISD fires. The base model showed good correlation to temperature data obtained from experimental testing. The FDS model accurately captured the fire development and therefore the base model was then further developed to investigate whether it is possible to model the suppression stage in FDS. The results from the full-scale test were used to calibrate the suppression model. The temperature response following the introduction of water into the model closely resembles that measured during the full-scale experiment. A parametric study was then performed to investigate the influence of varying discharge rates from the water supply point, as well as the distance from the water supply point on the required suppression duration. It was shown that there is a significant increase pertaining to the suppression duration as the discharge rate is decreased and the distance from the dwelling to the water source is increased. This of great concern, especially in environments such as informal settlements, which are characterized by high dwelling densities and dwellings which are generally constructed from combustible materials, thereby providing ideal conditions for rapid fire spread. Based on the results from the suppression models a minimum discharge rate of 23 lpm is recommended for a 3.85 MW ISD fire (as produced by a home of 2.4 x 3.6 m with a timber fuel load of 25 kg/m²). Further research is required of real fires when communities responded to fires, such that it can be identified when, and when not, local infrastructure was sufficient for suppressing fires.

Furthermore, it was shown that the effectiveness of the bucket brigade technique was substantially reduced for a 5.8 MW fire (as produced by a home of 2.4 x 3.6 m with a timber fuel load of 40 kg/m²).

The simulations for investigating the performance of the bucket brigade technique for a 5.8 MW fire showed that it is possible to extinguish the fire. However, the time required to initiate the temperature reduction within the dwelling is substantially longer and therefore it is almost certain that the fire will have spread to adjacent dwellings, thereby potentially restricting residents from accessing the dwelling of fire origin. The results obtained from the suppression models used during the parametric study should be interpreted with care due to numerous limitations associated with suppression modelling within FDS. FDS does not account for the breakdown of water bodies i.e. the water droplet size remains constant throughout the entire simulation. Furthermore, as previously mentioned, in FDS fuel cooling is achieved by means of an empirical coefficient known as the “extinguishing coefficient”, which is responsible for the exponential decay of the burning rate. The reduction of the burning rate is therefore linked to the water mass per unit area of the fuel surface as well as an empirical coefficient which needs to be determined experimentally and therefore makes suppression modelling in FDS not always suitable for predictive simulations.

5.3. Future research and recommendations

Informal settlement fires are an emerging field of interest with many facets which are yet to be investigated. By investigating different aspects associated with informal settlement fires, it becomes possible to formulate a better understanding of the behaviour of informal settlement fires. The work discussed in this thesis, as well as the proposed work to be conducted in the future will potentially assist in improving fire safety within informal settlement communities. As mentioned from the onset, the work conducted in this thesis forms part of a larger research investigation. Currently, work is being performed by fellow co-researchers focussing on the topics listed below, and this thesis provides insight for these topics in terms of understanding suppression and fire behaviour:

- Forensic investigations of fire disasters to understand fire spread mechanisms within informal settlements and human behaviour during informal settlement fires [1].
- Development of a full-scale testing methodology for assessing passive fire protection products [2].

The performance of suppression systems on multiple burning dwellings should be investigated in the future to determine the feasibility of large-scale implementation into informal settlement communities. The influence of thermal feedback, reduced accessibility and reduced water supply will be accounted for when conducting suppression tests on multiple ISDs. These full-scale testing methodologies assist national and municipal agencies in terms of planning and decision making, thereby acting as a tool which makes it possible to make progress with the issue of fire safety in informal settlement communities.

For future research, it is recommended that the mass loss rate or HRR during full-scale experiments is measured, since these parameters are critical input parameters for the development of accurate FDS models. Furthermore, for future work it would be recommended that an investigation on the influence of introducing a secondary mesh for the burners when adopting the simplified FDS model used in this thesis should be carried out. The burners would have a more refined mesh size compared to the mesh used for the model obstructions. The use of multiple meshes will influence the simulation time negatively, but it will potentially capture the temperature response more accurately, following the introduction of water into the model, since the reduction of the burning rate of the burner will be limited to a smaller area i.e. only where the water is situated instead of cooling a larger portion of the burner.

5.4. Closing comments

This thesis has proposed a novel testing methodology for evaluating the performance of various existing suppression systems for the use in post-flashover informal settlement fires. The proposed testing methodology does not aim to solve the issue of fires in informal settlement communities but rather serves as a tool for local and national authorities, which can assist during the decision-making process when considering what steps to take in the future. The proposed testing methodology was designed so that it can be used by a wide audience including national authorities, municipalities, non-profitable governmental organisations, fire brigades etc., since it does not require the use of sophisticated or expensive testing equipment. Furthermore, the work discussed in this work has shown that it is possible to model the fire response following the initiation of the suppression phase and therefore acts as a platform for future work. Since our knowledge regarding informal settlement fires is currently limited, care should be taken when attempting to model the suppression of these type of fires with high levels of accuracy/certainty. Additional research is required to further develop numerical models, which include various material properties of ISDs, fuel loads and properties, ventilation conditions, human response etc.

5.5. References

[1] N. Flores Quiroz, “Forensic investigations of fire disasters to understand fire spread mechanisms within informal settlements and human behaviour during informal settlement fires,” Stellenbosch University, 2021.

[2] V. Narayanan, “Development of a full-scale testing methodology for assessing passive fire protection products,” Stellenbosch University, 2021.

Appendix: FDS code for the development of the benchmark model

The FDS code pertaining to the development of the benchmark model produced in Chapter 4 is provided below, thereby allowing other researchers to validate the models utilised throughout this investigation. It is not possible to list each time step for the HRRPUA of the cardboard lining and representative timber burner and therefore the time steps have subsequently been omitted from the FDS input file.

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Generated by PyroSim - Version 2019.1.0515

25 Jul 2019 6:42:24 PM


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    H=6.2,

    O=2.5,

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